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SEDIMENTOLOGY AND PETROLEUM GEOLOGY OF THE LOWER CRETACEOUS GRAND RAPIDS FORMATION COLD LAKE OIL SANDS AREA, ALBERTA

©

by

BRUCE M. BEYNON

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA
SPRING 1991

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Bruce M Beynon

13523-129 Street
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T5L 1K4

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Supervisor

C R Stelck

Date Feb 1 1991

ABSTRACT

The Lower Cretaceous Grand Rapids Formation, within the Cold Lake oil sands area consists of complex succession of shoal-water deltaic and marginal marine deposits. The most characteristic feature of the Grand Rapids Formation is the vertical repetition of facies and depositional environments. Within the study area, the Grand Rapids Formation can be subdivided into six flooding surface bounded lithosomes. Each lithosome, is characterized by an overall shoaling-upwards succession of facies, and records local shoreline response to variations in sediment influx, changes in the rate of subsidence and changes in relative sea level. Internally, each lithosome is characterized by a predictable vertical and lateral succession of facies which reflect the depositional processes operating during that particular interval of sedimentation. Overall, these six lithosomes are arranged into a progradational stacking pattern reflecting the continual basinward shift in the locus of active shoreline sedimentation throughout the deposition of the Grand Rapids Formation.

Within the study area the Grand Rapids Formation is estimated to contain 3500 x 10^6 m^3 of oil in place and 3366 x 10^6 m^3 of gas in place. Hydrocarbon distribution is primarily related to the distribution of porous and permeable sandstone and structural elevation. Sandstone geometry and reservoir quality are, in turn, related to primary depositional processes. The quantity or thickness of the bitumen saturated column that is developed is related to the structural attitude of the reservoir sandstone. Structure, for the most part, is related to post-depositional solution of the Prairie Evaporite Formation. Within the study area, the regional southwesterly dip of the Mannville Group is interrupted by a salt solution trough. Superposition of this trough upon the regional dip of the Western Canadian Sedimentary Basin produces a prominent north trending ridge. The majority of the hydrocarbons within the study area are trapped in structures associated with this feature.

The current study emphasizes the integration of physical and biogenic sedimentary structures to the sedimentological analysis of the Grand Rapids Formation. This process

sedimentologic approach, when integrated with traditional subsurface methods, will increase the predictability of ancient depositional environments, and ultimately improve the resolution of reservoir and non-reservoir units.

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CHAPTER 1

1.1 Introduction

The Lower Cretaceous oil sands deposits of Western Canada (Fig. 1.1), Athabasca, Cold Lake, Peace River and Wabasca, form a discontinuous trend in northeast and east central Alberta. Presently the Cretaceous oil sands deposits are estimated to contain 225,800 x 10^6 m^3 (1610 billion barrels) of oil-in-place (ERCB, 1989). The majority of which are contained within the Lower Cretaceous Mannville Group. The Cold Lake oil sands area is the second largest of the Canadian deposits, covering aproximately 9000 km^2 and containing an estimated 34,960 x 10^6 m^3 (220 billion barrels) of oil-in-place (ERCB, 1989). Hydrocarbons are found within all three formations of the Mannville Group; in ascending order these are the: McMurray, Clearwater and Grand Rapids formations. To date, the majority of the exploitation and development within the Cold Lake oil sands area has been concentrated on the Clearwater Formation. However, the majority of the reserves are contained within the Grand Rapids Formation which is estimated to contain 19, 050 x 10^6 m^3 (120 billion barrels) of oil-in-place (ERCB, 1989).

Considering the vast reserves contained within the Grand Rapids Formation, it represents an important target for future development. Successful economic exploitation of this resource, however, requires a thorough understanding of the sedimentologic, stratigraphic and structural controls that influence hydrocarbon distribution. Since the Mannville Group strata of northeastern Alberta have undergone minimal post-depositional burial, and, therefore, limited post-depositional modification (cementation, clay authigenesis, pressure solution *etc.*), principal reservoir parameters such as bitumen saturation, porosity and permeability are, for the most part, related to primary litho-facies distribution (Mossop, 1980). Consequently, detailed, integrated facies models are an essential requirement for the most efficient development of the Grand Rapids Formation. To this end, the primary objective of this study was to determine what processes and depositional environments were responsible for the distribution of facies

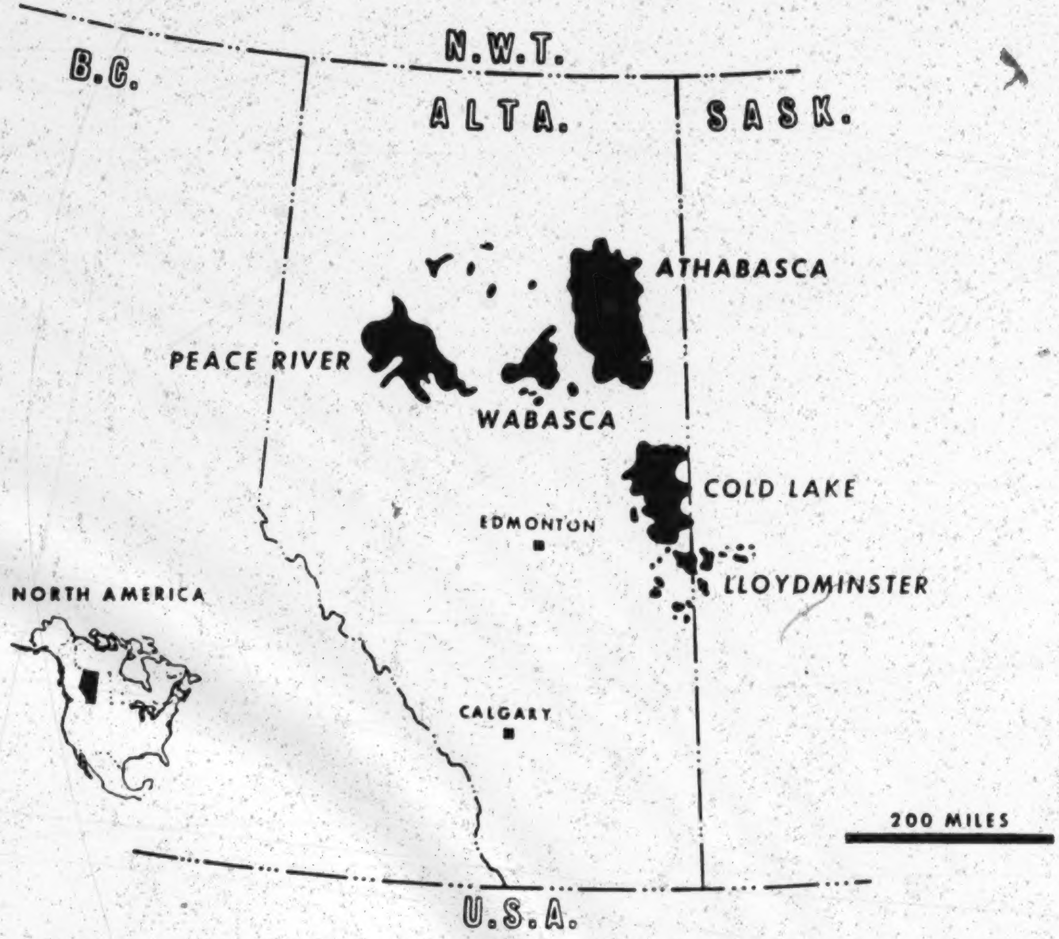


Figure 1.1 Major Lower Cretaceous oil sands and heavy oil deposits of western Canada (After Jardine, 1974).

encountered within the Grand Rapids Formation.

1.2 Study Area and Well Control

The study area is located in the eastern portion of the Cold Lake oil sands area (Fig. 1.2), and it is bounded by to the south and north and to the east and west by Townships 60 to 63 and Ranges 1 to 3 west of the Fourth Meridian respectively, a total area of 1200 km^2. Forty-six drill cores and 241 well logs were examined to delineate facies, determine depositional processes, establish depositional environments and the distribution of hydrocarbons within the Grand Rapids Formation.

1.3 Methodology and Objectives

The primary objectives of the study were:

(1) to establish a stratigraphic framework for the Grand Rapids Formation;
(2) to define sedimentary facies and facies relationships within the Grand Rapids Formation;
(3) to determine the lateral and vertical extent of these facies;
(4) to define any structural controls that may have influenced the the distribution of the Grand Rapids Formation facies;
(5) to develop a model for the depositional history of the Grand Rapids Formation; and
(6) to determine how these five criteria are related to the distribution of bitumen within the Grand Rapids Formation.

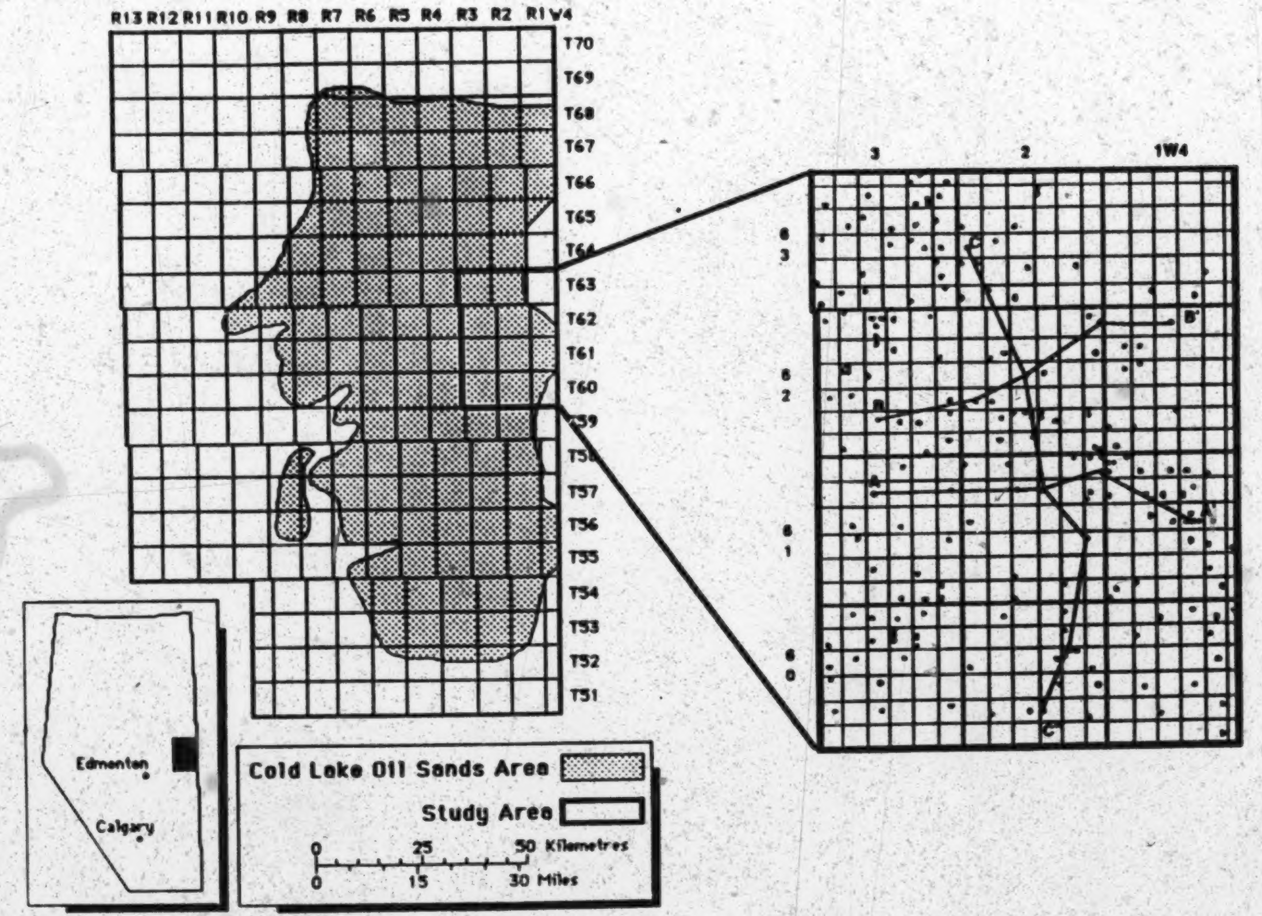


Figure 1.2 Study area location map illustrating core and wellbore control utilized in the study of the Grand Rapids Formation. Also location of stratigraphic cross-sections A-A', B-B' and C-C'.

In order to facilitate this study, a multidisciplinary approach utilizing ichnology, physical sedimentology and well logs was employed. The objectives were accomplished by creating an integrated database consisting of drill core descriptions, well logs and core analyses.

(1) Drill core description

A total of 46 drill cores (36 of which are included in the Appendix) were described in detail to ascertain the depositional environment of the Grand Rapids Formation. All drill cores were accessed at the Energy Resource Conservation Board (ERCB) core research facility in Calgary, Alberta. Drill cores were examined with particular reference to the following properties:

(1) lithology
(2) grain size and sorting characteristics;
(3) biogenic and physical sedimentary structures;
(4) bedding styles and bed thickness;
(5) nature of bedding contacts and bounding surfaces;
(6) heirarchical relationship of bedding units
(7) relative intensity of bioturbation; and
(8) relative degree of bitumen saturation.

(2) Well logs

A database consisting of well logs from 241 wells was used to supplement the information distilled from drill core descriptions and interpretations. Well logs were used to determine the three-dimensional distribution of facies and facies associations recognized from drill cores. Petrophysical well logs were also utilized to estimate paleotopography and to determine the present-day structural attitude of strata in the vicinity of the study area. Once calibrated with core analysis data, the well logs were also utilized to map the distribution of potential reservoir and non-reservoir strata within the study area.

1.4 Previous Work

Although the Cold Lake oil sands area represents the world's third largest oil sands accumulation, very few published studies have concentrated on the sedimentology and stratigraphy of this deposit, notable exceptions include Kendall (1977) and Towson, (1977). This is largely because of the fact that the bulk of the bitumen presently extracted in the Cold Lake oil sands area has been from the Clearwater Formation, and, consequently, most site specific geological studies in the Cold Lake area have focused on the Clearwater Formation. In contrast, there have been a number of studies outside of the Cold Lake oil sands area which have focused on the Grand Rapids Formation or equivalent strata. A great wealth of studies have concentrated on the Mannville Group succession in the Lloydminster heavy oil area, such as those of Haidl (1980,1984), van Hulten (1984) van Hulten and Smith (1984), MacEachern (1984,1989), Putnam (1980, 1982, 1988), Putnam and Oliver (1980) and Smith (1984). Furthermore, there have been a number of detailed outcrop and subsurface studies which have concentrated on the Grand Rapids Formation in the Wabasca oil sands area (Kramers, 1974, 1982; Keeler, 1980; Stelck and Kramers, 1980). Additionally there have been a number of comprehensive regional studies of the Mannville Group which have included the Grand Rapids Formation (*cf.* Williams, 1963; Mellon, 1967; Jackson, 1984; Masters, 1984; among others).

1.5 Stratigraphy and General Geology

In the Cold Lake oil sands area the Mannville Group comprises an Aptian to early Albian (Stelck and Kramers, 1980) siliciclastic succession of poorly lithified sediments which rest unconformably above Upper Devoninan carbonates of the Woodbend and Beaverhill Lake Groups. The Grand Rapids Formation, Lower Albian in age (Stelck and Kramers, 1980), is the uppermost of the three formations which comprise the Mannville Group in central and eastern Alberta (Fig. 1.3). It is characterized by a succession of fine- to medium-grained feldspathic sandstones with intervening beds of laminated glauconitic sandstone and silty shale with some coal beds (Carrigy, 1971). The Grand Rapids Formation conformably overlies the Clearwater Formation; this contact has been described

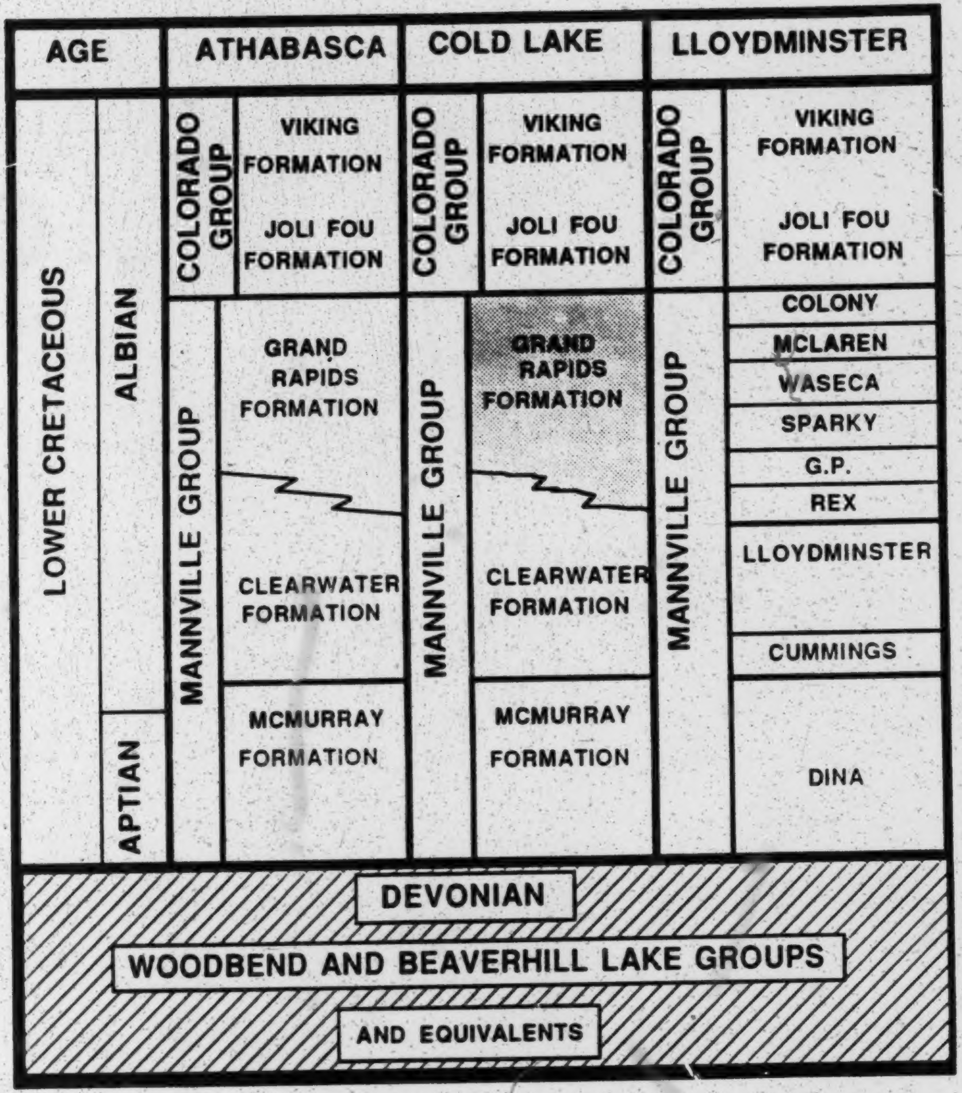


Fig. 1.3 Stratigraphic terminology chart of the Mannville Group of east-central Alberta and west central Saskatchewan. (Note the Mannville Group stratigraphic terminology utilized in the Lloydminster area is an informal terminology based on current industry usage.)

as gradational and diachronous (Mellon, 1967; Carrigy, 1971; Kramers, 1974). The Grand Rapids Formation is, in turn, disconformably overlain by earliest Late Albian shales of the Joli Fou Formation. In the subsurface of the Cold Lake oil sands area the Grand Rapids Formation is relatively continuous between Townships 53 to 66 and Ranges 1 to 10 west of the Fourth Meridian (Ottrim and Evans, 1977). Within the study area the Grand Rapids Formation forms an eastward thickening siliciclastic wedge in which isopach values range from a minimum of 88 m in the southwest to a maximum of 114 m in the eastern portion of the study area. Within the study area the Grand Rapids Formation is encountered between depths of 297 m and 439 m.

1.6 Mannville Group Nomenclature

The first geologic descriptions of the Mannville Group began with the works of R.G. McConnell in which he described the Lower Cretaceous section along the banks of the Athabasca River near Pointe La Birche. McConnell (1893) introduced the terms "Clearwater" and "Grand Rapids" to describe two litho-stratigraphic units;. the "Clearwater" Formation referred to a portion of the section composed predominantly of shale with greenish, glauconitic sandstones, and the "Grand Rapids" Formation referred to a complex succession of interbedded greywackes, siltstones and shales with some minor coal beds overlying the Clearwater Formation. Shortly thereafter, McLearn (1917) examined the Lower Cretaceous section along the Athabasca River and proposed the name "McMurray" Formation for the bituminous sands which underlie the green glaucontic sandstones of the Clearwater Formation.

The term "Mannville" was introduced by Nauss (1945) in reference to the Lower Cretaceous section from the subsurface of the Vermilion area. In the context of Nauss (1945), the "Mannville" was given formational status and defined as the complex siliciclastic succession lying between the sub-Cretaceous unconformity and the marine shales of the Joli Fou Formation. Wickenden (1948) recognized that the Mannville Formation was continuous into western Saskatchewan. Badgley (1952) proposed that the Mannville Formation should be elevated to group status, and subsequently proposed the subdivision of the Mannville Group into, in ascending order, the McMurray, Clearwater and Grand Rapids formations.

Shortly after the works of Nauss (1945), Wickenden (1948) and Badgley (1952) were published, the intra-Mannville Group correlation schemes of east-central Alberta and west-central Saskatchewan diverged. In the Lloydminster area, the original stratigraphic nomenclature proposed by Nauss (1945), Wickenden (1948) and Badgley (1952) were modified by the petroleum industry into an informal stratigraphic framework which currently evokes a 9-fold subdivision of the Mannville Group. Present usage recognizes in ascending stratigraphic order the Dina, Cummings, Lloydminster, Rex, General Petroleums, Sparky, Waseca, McLaren and Colony formations. This stratigraphic scheme is lithological in nature and relies upon the recognition of sub-regional marker beds, coal seams and other lithologic/well log markers for formational designation, but is specific to particular geographic locations (Putnam and Klovan, 1987; Putnam, 1988). Based on regional stratigraphic correlations, Jardine (1974) suggested that the Dina Formation of the Lloydminster area was the stratigraphic equivalent of the McMurray Formation; the Cummings and Lloydminster formations were equivalent to the Clearwater Formation; and the Rex, General Petroleums, Sparky, Waseca, McLaren and Colony formations were considered to be stratigraphically equivalent to the Grand Rapids Formation.

1.7 Application of a Genetic Stratigraphic Framework to the Grand Rapids Formation

The ultimate aim of facies analysis is to interpret depositional processes, and subsequently propose a depositional model which most accurately predicts the observed lateral and vertical facies variations. However, prior to facies correlations and mapping of three dimensional facies variations it is necessary to establish a time-stratigraphic or genetic stratigraphic framework for the succession to ensure that only time-equivalent strata are correlated. In the Cold Lake oil sands area the Grand Rapids Formation is essentially devoid of preserved body fossils, thus precluding the development of a chronostratigraphic framework based upon biostratigraphic correlations. Futhermore, other potential isochronous markers, such as bentonite beds, have not been documented from the

Mannville Group (Haidl, 1984; Putnam, 1988). An alternative method that may be utilized to construct a working chronostratigraphic framework for the sedimentological analysis of the Grand Rapids Formation involves the utilization of sequence stratigraphic principles.

Sequence stratigraphy is the analysis of repetitive, genetically related depositional units bounded by surfaces of non-deposition, erosion or their correlative conformities (Van Wagoner *et al.*, 1988). The stratigraphic framework proposed for the Grand Rapids Formation involves the recognition and delineation of flooding surface bounded depositional units, which within this study are referred to as lithosomes (*cf.* Moore, 1957; Nummedal and Swift, 1987). Essential to the utilization of this genetic stratigraphic approach is the recognition of flooding surfaces. Flooding surfaces separate strata of different ages and record periods of non-deposition or very slow sedimentation with or without concomitant submarine erosion (Galloway, 1989). The surface produced by transgression or flooding is one of the most readily recognizable surfaces and can be easily correlated from drill core to well logs, outcrop and seismic (Haq *et al.*, 1987, 1988; Van Wagoner, 1988; Galloway, 1989). In drill cores from the Grand Rapids Formation, flooding surfaces are recognized by a distinct change in the nature of the ichnofossil assemblages, which reflect increases in salinity and/or water depth. Once identified in drill core, the flooding surfaces can be readily correlated to well logs where core control is not available. Flooding surfaces, although they may be time-transgressive, can be considered to approximate isochrons, particularly at the subregional scale of this study. Seven flooding surfaces were recognized within the study area, and have been used to subdivide the Grand Rapids Formation into six lithosomes or progradational-transgressive couplets (Figs. 1.4, 1.5 and 1.6). Internally each lithosome records a period of progradation and aggradation terminated by a period of flooding or transgression. These lithosomes, as defined in the context of this discussion, are similar to the parasequences of Van Wagoner *et al.* (1988). However, this terminology was not utilized because parasequences are part of a hierarchical arrangement of bounding surfaces of which regional unconformities or sequence boundaries are the key elements. Such regional unconformities, which necessitate periods of subaerial erosion, could not be recognized due to the site specific nature of this study. The genetic stratigraphic approach

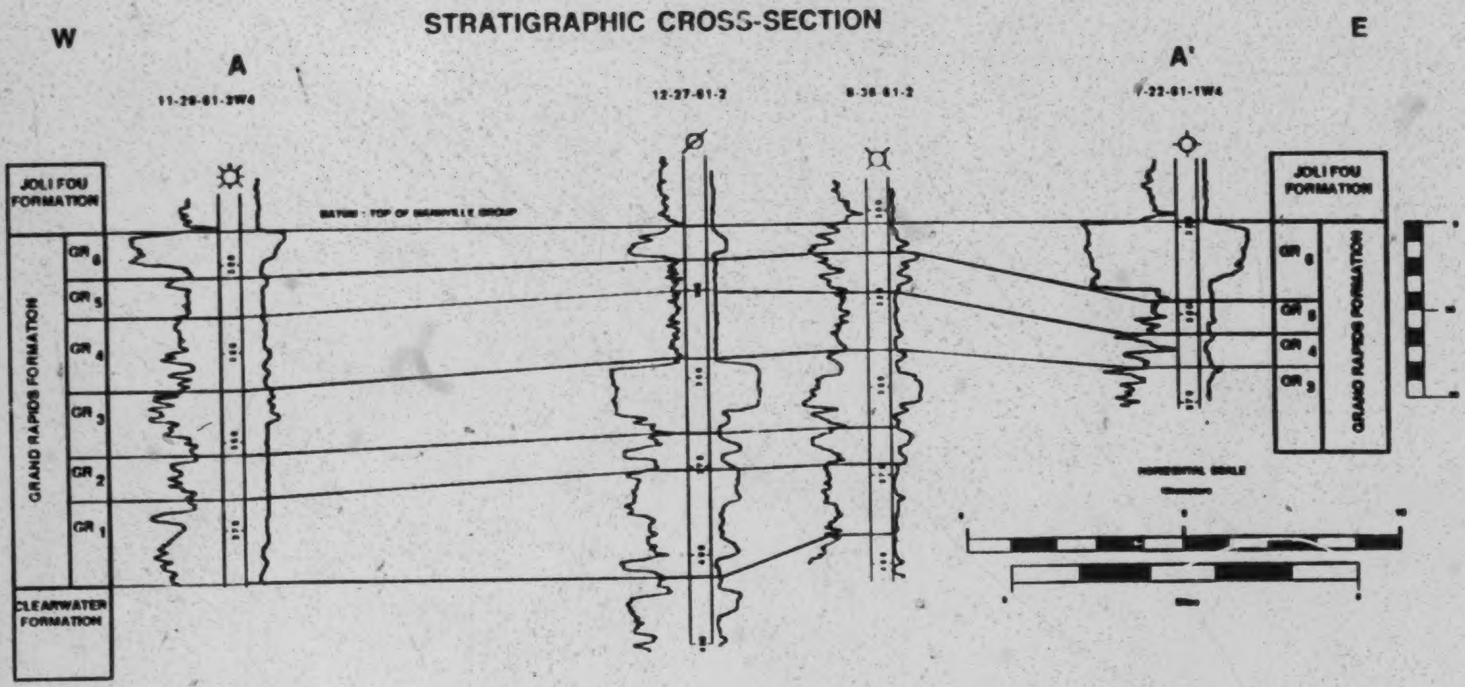


Figure 1.4 Stratigraphic cross-section A-A' illustrating the subdivision of the Grand Rapids Formation into six flooding surface-bounded depositional units termed lithosomes. The gamma ray log is displayed on the left track and the induction log is displayed on the right track. Depths are in meters.

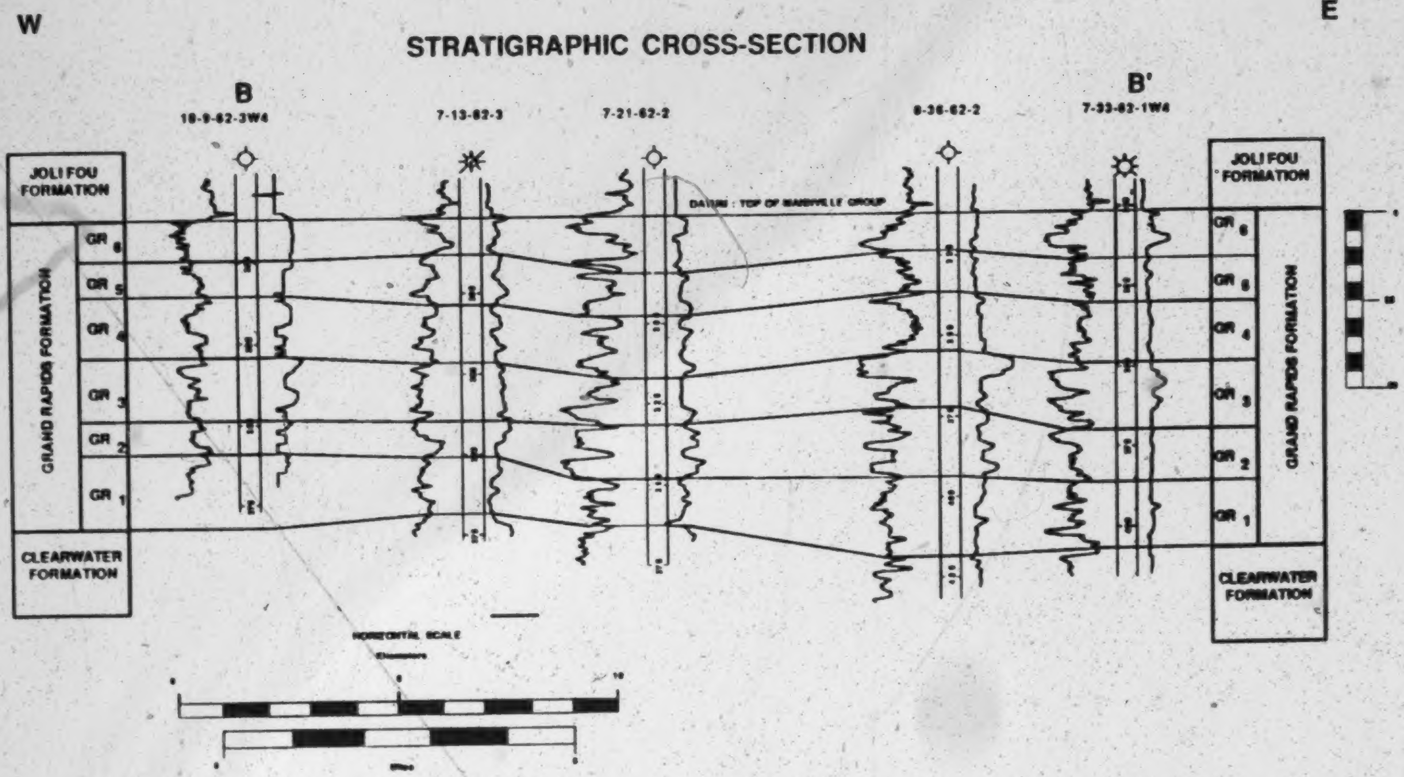


Figure 1.5 Stratigraphic cross-section B-B' illustrating the subdivision of the Grand Rapids Formation into six flooding surface-bounded depositional units termed lithosomes. The gamma ray log is displayed on the left track and the induction log is displayed on the right track. Depths are in meters.

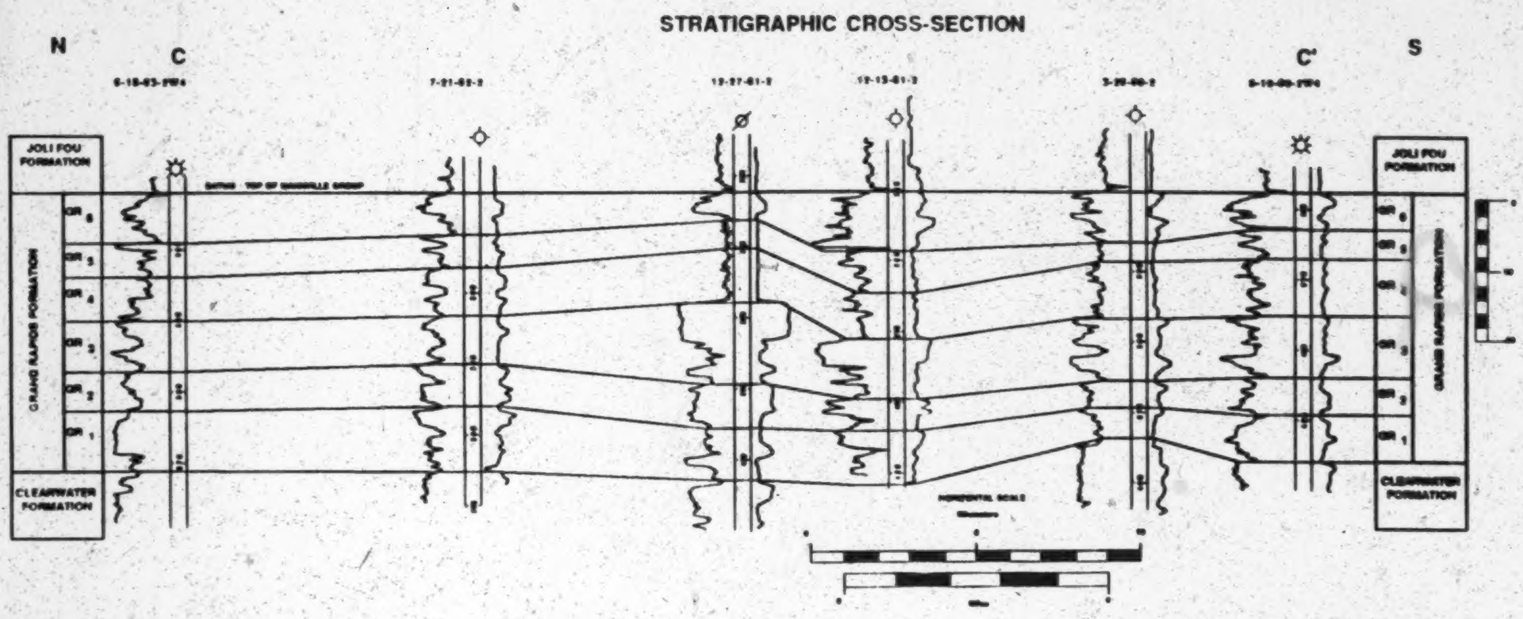


Figure 1.6 Stratigraphic cross-section C-C' illustrating the subdivision of the Grand Rapids Formation into six flooding surface-bounded depositional units termed lithosomes. The gamma ray log is displayed on the left track and the induction log is displayed on the right track. Depths are in meters.

utilized for this study of the Grand Rapids Formation recognizes periods of sediment influx and associated coastal progradation as the principal depositional episodes, regardless of the cause (sea level fall, increased sediment input or decreased subsidence rate) (Galloway, 1989). The utilization of such a genetic stratigraphic approach facilitates regional correlations between the Cold Lake and Lloydminster depositional subbasins. Preliminary regional correlations suggest that the GR_1 through GR_6 lithosomes are correlative with the Rex through Colony formations recognized in the Lloydminster area.

CHAPTER 2 FACIES DESCRIPTIONS AND INTERPRETATIONS

2.1 Introduction - The "Facies" Concept

The facies concept is one of the most extensively utilized concepts in sedimentary geology, however, it is also potentially the most frequently misused geologic concept. The original definition is very clearly defined, however, it has been ignored by a large proportion of the geological community, particularly that of North America.

Facies is derived from the Latin word *"facies"* or *"facia"* which implies the external appearance, look, aspect or condition of an object (Teichert, 1958; Walker, 1984). It was first introduced in a geological context by Nicolaus Steno in 1669 to represent the entire aspect of the earth's surface during an interval of geologic time. However, it was not until 1838, through the works of Swiss geologist Amand Gressly, that facies was considered in a stratigraphic context. Gressly's (1838, in Teichert, 1958) original definition of facies reads as follows:

> "To begin with, two principle facts characterize the sum total of the modifications which I call facies or aspects of a stratigraphic unit: one is that a certain lithologic aspect of a stratigraphic unit is linked everywhere with the same palaeontological assemblage, the other is that from such an assemblage fossil genera and species common in other acies are invariably excluded"

With this in mind, it becomes clear that the term facies was originally defined to represent the expression of the collective lithologic and palaeontologic characteristics of a sedimentary rock unit. These characteristics, in turn, are utilized to interpret a depositional environment for that particular rock unit. Facies, therefore, was originally defined to represent an abstraction or expression of the primary properties of a rock body, not the rock body itself (Teichert, 1958). Although paleoenvironmental interpretations are the primary goal of facies descriptions, genetic interpretations should not be included within the

the definition of facies; because as stated by Teichert (1958) "the environment is not the facies, but it is the environment that produces the facies". Therefore facies are defined on purely descriptive grounds. Objective facies descriptions are used to interpret paleohydrodynamic and paloecological conditions. Just as one sedimentary structure is not indicative of a depositional environment, a single facies is not diagnostic of any particular depositional environment; therefore, the sequence or association of facies is ultimately used to interpret processes and environments of deposition.

2.2 Facies Descriptions and Interpretations

Seven facies were recognized from Grand Rapids Formation drill core. They are as follows:

Facies 1 Mudstone
    Subfacies 1a Dark grey-green laminated mudstone
    Subfacies 1b Dark to light grey interlaminated mudstone
    Subfacies 1c Dark grey (carbonaceous) thinly laminated mudstone
    Subfacies 1d Carbonaceous mudstone

Facies 2 Bioturbated sandstone
Facies 3 Small-scale cross-stratified sandstone
Facies 4 Large-scale cross-stratified sandstone
Facies 5 Planar-laminated to low-angle cross-stratified sandstone
Facies 6 Massive sandstone

Facies 7 Heterolithic facies
    Subfacies 7a Intercalated sandstone and mudstone
    Subfacies 7b Interbedded sandstone and mudstone
    Subfacies 7c Mixed (homogenized) sandstone and mudstone

2.2.1 Facies 1 - Mudstone

Facies 1 is divided into four subfacies on the basis of bedding style and preserved sedimentary structures.

2.2.2 Subfacies 1a - Dark grey-green laminated mudstone

Description:

Subfacies 1a is characteristic of the Joli Fou Formation. It is represented by dark grey to olive-green, thinly laminated mudstones which contain abundant mollusc shell fragments which are commonly encountered in distinct shell-hash zones. Due to the thinly laminated nature of this facies it is typically rubbled and very poorly preserved. Sideritic mudstone concretions and siderite-stained zones are common throughout subfacies 1a. Thin (0.2-2 cm) siltstone or very fine-grained sandstone lenses, as well as thicker sandstone interbeds (up to 10 cm) are locally common. Siltstone and sandstone interbeds are typically massive, but planar-laminated or cross-stratified beds have also been observed. Beds of this subfacies are typically devoid of biogenic sedimentary structures. The nature of the basal contact of this subfacies is highly variable, however, it is always sharp and is commonly represented by an erosive surface overlain by siderite- and/or calcite-cemented mudstone intraclasts.

Interpretations:

The mudstone beds of subfacies 1a are interpreted to be suspension deposits of fine, hemipelagic sediments emplaced in a low-energy setting. Local siltstone and sandstone interbeds, on the other hand, indicate that quiet-water suspensiondeposition was periodically interrupted by episodic, higher-energy events which resulted in the deposition of thin interbeds and lenses of coarse clastic material. Some of the very fine-grained sandstone and coarse-grained siltstone beds display planar-laminations and small-scale cross-stratification indicative of tractional transportation or wave reworking of suspension deposited siltstone and sandstone. However, the majority of the sandstone and coarse siltstone interbeds do not appear to display any evidence of primary lamination or cross-stratification, suggesting that they were, most probably, deposited from suspension without post-depositional tractional transport. The absence of biogenic sedimentary structures within beds of this subfacies suggests that the benthic population was subjected to unfavourable environmental conditions (*e.g.* low salinity, low oxygen, low nutrient availability).

2.2.3 Subfacies 1b - Interlaminated mudstone

Description:

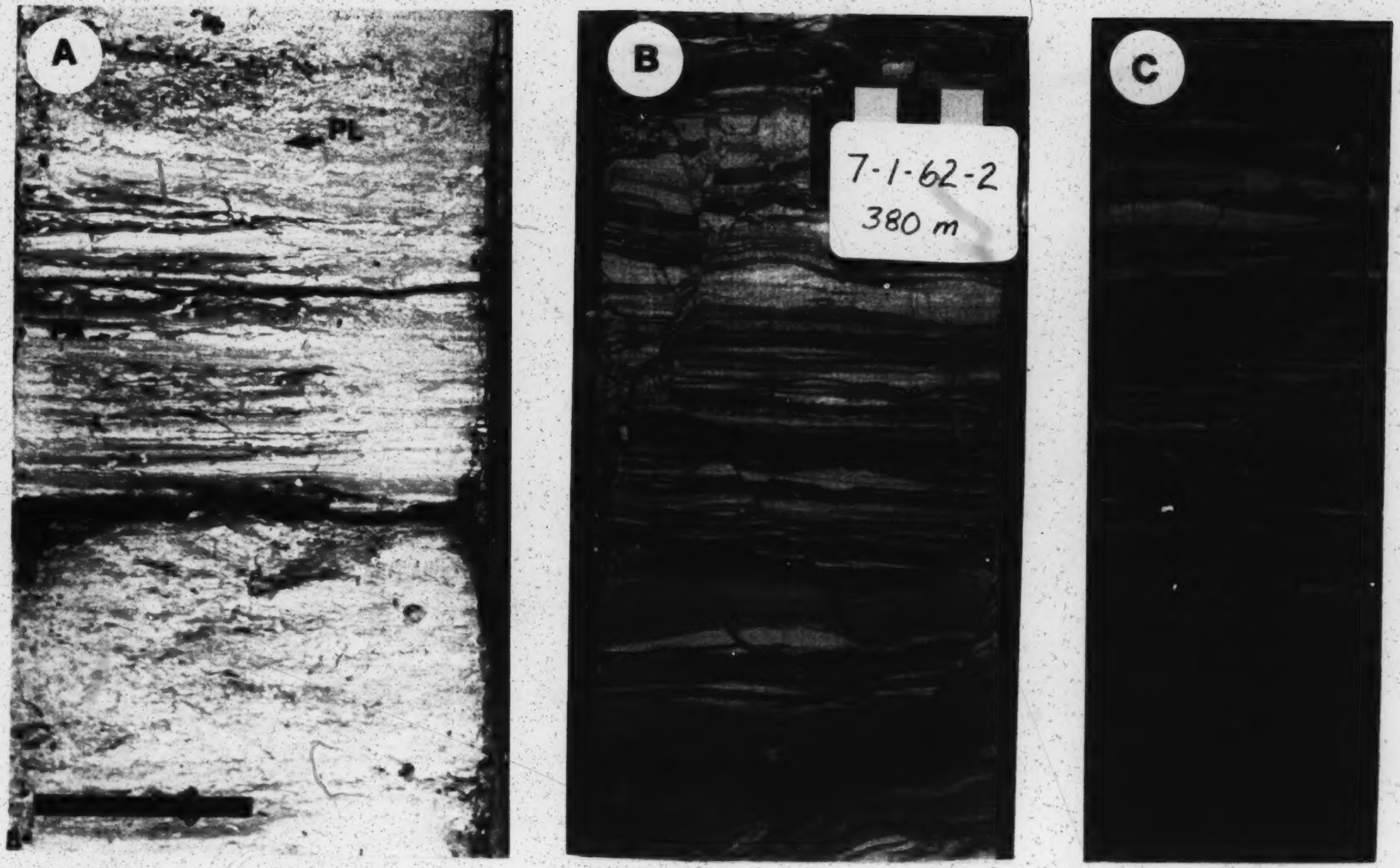
This subfacies is characterized by millimeter- to centimeter-scale alternations of dark mudstone and light coloured, silty, mudstone. The basal contact of this subfacies is always sharp and planar. Typically, the light and dark coloured mudstones are arranged into distinct, 3 to 25 mm thick, fining-upwards couplets giving this subfacies a distinct "varved" appearance (Fig. 2.1a-c). A typical couplet consists of an erosive basal contact, a pale coloured silty mudstone lower unit and an upper dark-coloured massive mudstone unit. Internally, the lower unit may be normally graded or, less commonly, parallel laminated. The upper unit consists of massive to thinly laminated, dark coloured, carbonaceous-rich mudstones. The transition from the lower to upper unit is typically gradational. Syneresis cracks are common, particularly within the upper dark coloured mudstone unit (Fig. 2.1c). The relative degree of bioturbation is highly variable, ranging from non-bioturbated to intensely bioturbated (Fig. 2.1a); although, non-bioturbated or poorly bioturbated beds predominate (Fig. 2.1b and c). This subfacies is characterized by low to very low diversity ichnofossil assemblages dominated by *Teichichnus*, *Planolites* and *Skolithos*, associated forms include *Asterosoma*, *Palaeophycus* and rarely, *Rhizocorallium*.

Figure 2.1 Subfacies 1b

a) Interlaminated mudstones with alternating thoroughly bioturbated and non-bioturbated to weakly bioturbated zones. The thorougly bioturbated zones are characterized by high density ichnofossil assemblages dominated by *Planolites* (PL), associated ichnofossils include *Palaeophycus* (PA) and *Skolithos*. The photograph is from 6-6-62-1W4, 357.5m (GR_4 lithosome). Scale bar gradations are in centimeters.

b) Interlaminated mudstones, illustrating the characteristic arrangement of mudstone into sharp-based, fining-upwards couplets of light coloured silty mudstones and dark coloured carbonaceous mudstones. Some rare isolated *Planolites* burrows are present in the dark coloured carbonaceous mudstones. The photograph is from 7-1-62-2W4, 380 m (GR_3 lithosome). Scale bar gradations are in centimeters.

c) Interlaminated mudstones with abundant syneresis cracks (SY), isolated *Planolites* (PL) burrows and soft sediment deformation structures. The photograph is from 5-10-60-2W4, 357.5 m (GR_5 lithosome). Scale bar is 5 cm.


A
PL
B
7-1-62-2
380 m
C

Interpretations:

The fine-grained nature of subfacies 1b reflects the process of suspension settling of mud in a low-energy depositional setting. The gradational interlamination of dark, carbonaceous mudstone and light, silty mudstone suggest that the hydrodynamic conditions fluctuated regularly. The dark, massive to poorly laminated mudstones, which comprise the upper portions of the fining-upwards couplets, are interpreted to reflect background, "fairweather" mud deposition. The lighter-coloured, silty mudstones are interpreted to indicate mud and silt deposition under higher-energy conditions associated with storms and/or floods. Internally, these coarse units are characterized by normal grading or planar-laminations suggesting deposition from suspension without any tractional transport. The regular, varved-like intercalation of mudstone and silty mudstone suggests that these perturbations were of minor intensity but occurred regularly.

The presence of syneresis cracks in the upper dark silty mudstones provides some indication of the ecological-environmental conditions during deposition of this subfacies. Syneresis cracks are sedimentary structures which have been shown to develop at the sediment-water interface in response to extreme salinity fluctuations (Burst, 1965; Plummer and Gostin, 1981). In sedimentary environments, salinity fluctuations may be related to periods of high freshwater discharge into a brackish or marine receiving basin. Fluctuations of significant magnitude would impose significant stresses on the benthic community. Therefore, extreme salinity gradients should be preserved and reflected in the distribution of ichnofossils.

The low ichnotaxonomic diversity of this subfacies is interpreted to reflect harsh ecological conditions associated with variable salinity. Conditions of fluctuating and variable salinity are typical of brackish water settings. In general brackish water ichnofossil assemblages are characterized by: (1) low diversity; (2) reduced size compared to respective fully-marine counterparts; (3) an assemblage that is representative of an impoverished marine assemblage; (4) the predominance of morphologically simple horizontal and vertical structures; and (5) can be considered to represent a mixed *Skolithos* - *Cruziana* ichnofacies (Ekdale *et al.*, 1984; Wightman *et al.*, 1987). These characteristics imply that salinity may have been the predominant factor dictating the distribution of ichnofossils.

2.2.4 Subfacies 1c - Light grey laminated to massive mudstone

Description:

Subfacies 1c consists of thinly laminated to massive, silty mudstones with laminae and interbeds of coarse siltstone and very fine-grained sandstone (Fig. 2.2 a-c).The basal contact is typically gradational and rarely sharp and planar. The mudstones are thinly laminated or, less commonly, massive, and typically do not display the the distinct alternation of dark shaly and light silty beds observed within subfacies 1b. Sharp-based coarse siltstone and very fine- to fine-grained sandstone laminae and interbeds, up to 6 cm, are common. The majority of the sandstone beds, greater than 1cm, are small-scale cross-stratified; however, some of the thicker (2 to 6 cm) beds are planar-laminated at the base, grading upwards into small-scale cross-stratification. Generally, the top of the bed is represented by a thin (0.5 to 1 cm) cap of low amplitude, round-crested ripple form-sets. Thin (0.5-2 cm) siltstone and very fine-grained sandstone beds and laminae are typically planar laminated and rarely graded.

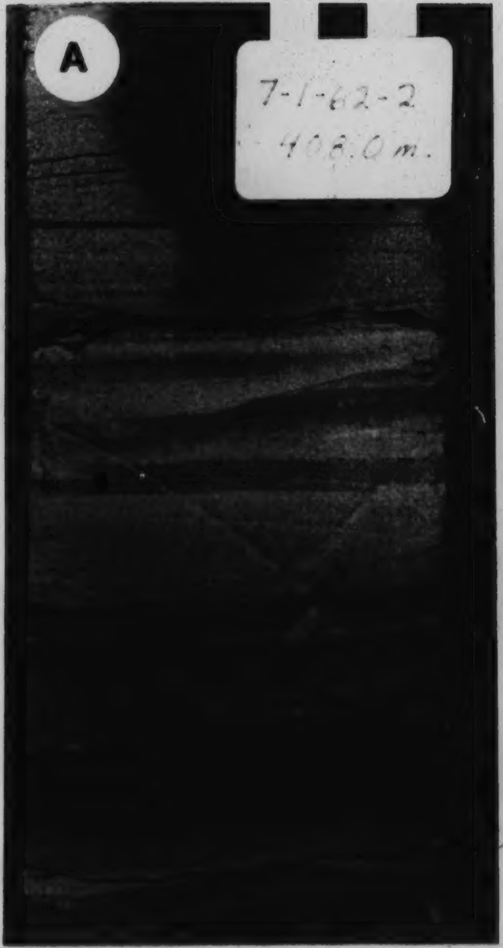
Siderite-cemented and siderite-stained zones are common. Carbonaceous debris is relatively abundant and typically is disseminated throughout the mudstone beds. Syneresis cracks are abundant. The relative intensity of bioturbation, although variable, is typically low to moderate and is characterized by low diversity, low density ichnofossil assemblages dominated by *Planolites*.

Figure 2.2 Subfacies 1c

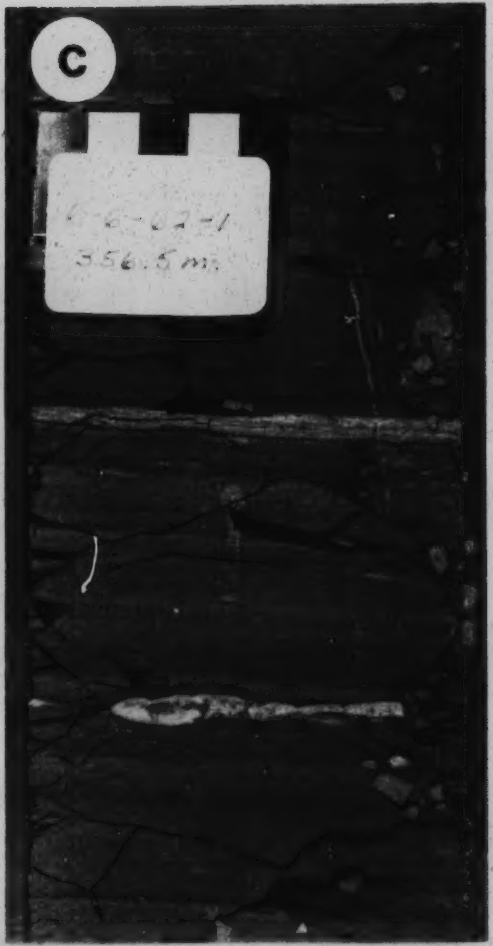
a) Laminated silty mudstones with sharp based fining-upwards beds of laminated siltstone and very fine grained sandstone. The photograph is from the basal portion of the GR_1 lithosome, 7-1-62-2W4, 408 m. Scale bar gradations are in centimeters.

b) Laminated mudstones with thin laminae of siderite. The photograph is from 5-10-60-2W4, 362 m (GR_5 lithosome). Scale bar gradations are in centimeters.

c) Laminated to poorly laminated mudstones. Note the presence of incipient siderite and the distinct absence of biogenic sedimentary structures. The photograph is from 6-6-62-1W4, 356.5 m (GR_4 lithosome). Scale bar gradations are in centimeters.


A
7-1-62-2
408.0 m.

B
5-10-60-2w4
362 m. 1187.5


C
6-6-62-1
356.5 m.

Interpretations:

The paleoenvironmental interpretation for subfacies 1c is similar to that proposed for subfacies 1b. The poorly laminated to massive mudstone beds were deposited from suspension during quiescent depositional conditions, and are interpreted to reflect "normal" fairweather mud accumulation. The sharp-based siltstone and sandstone beds represent event beds deposited during higher-energy conditions associated with storms or floods . The thin siltstone and very fine-grained sandstone beds, which display normal grading and planar-laminations, reflect deposition from suspension without any tractional transport. The thin, sharp-based small-scale cross-stratified siltstone and sandstone beds are interpreted to have been rapidly deposited from suspension, and subsequently, reworked by asymmetrical oscillatory waves and transported in small, sediment starved ripples. In the thicker sandstone beds the successions of planar-laminations grading upwards into small-scale wave ripple cross-stratification are interpreted to represent the episodic deposition from suspension and subsequent tractional transport under the influence of progressively waning asymmetrical oscillatory waves. The increased thickness of the sandstone beds and the presence of planar-laminations suggest deposition under more energetic conditions. Thus, the three types of sharp-based, event beds observed within this subfacies define a continuum of increasing energy conditions.

As with subfacies 1b, the low diversity and low density of ichnofossils is interpreted to reflect, stressed environmental conditions. Relative to subfacies 1b, both the diversity and density of ichnofossils decreases in subfacies 1c. This suggests that environmental stresses (*i.e.* salinity, oxygenation, nutrient availability) were more significant during deposition of subfacies 1c. The combination of syneresis cracks, low diversity/low density ichnofossil assemblages, the abundance of siderite and carbonaceous matter are interpreted to indicate deposition in a restricted, brackish water setting that was subject to periodic salinity reductions. Siderite precipitation occurs during the earliest stages of diagenesis of organic-rich mud (Gautier, 1982; 1984), and is enhanced by high concentrations of organic matter in a reducing setting. High suspension-settling rates combined with the incomplete oxidation of organic matter could produce oxygen-restricted, potentially anaerobic conditions. Therefore, the low diversity and density of ichnofossil observed within this subfacies is interpreted to reflect salinity- and oxygen-stressed depositional setting. The paleoecological significance of this ichnofossil association will be elaborated upon in Chapter 3.

The increase in the overall volume of sandstone incorporated within this subfacies relative to subfacies 1b suggests that the episodic or higher energy events which resulted in the deposition of the sandstone interbeds were both more frequent and more intense during deposition of subfacies 1c than during deposition of subfacies 1b. This suggests that subfacies 1c may have been deposited in a more shallow and energetic setting than that envisaged for subfacies 1b. Furthermore, the low density, monospecific ichnofossil assemblages combined with the abundance of syneresis cracks, siderite and carbonaceous material suggest deposition in an increased salinity stressed or restricted brackish water setting. This, combined with the overall lithologic similarity of subfacies 1c and 1b, suggests that subfacies 1c may represent a proximal equivalent of subfacies 1b.

2.2.5 Subfacies 1d - Carbonaceous mudstone

Description:

This subfacies is characterized by carbonaceous, dark grey, thinly laminated mudstones. The basal contact of this subfacies is always gradational, whereas, the upper contact is always sharp and planar. The most characteristic feature of this facies is the abundance of carbonaceous material which occurs as vertically-orientated rootlets, thin (1-5 mm) laminae and randomly distributed disseminated material (Fig. 2.3). Typically the carbonaceous mudstones are parallel-laminated near the base of the bed, becoming

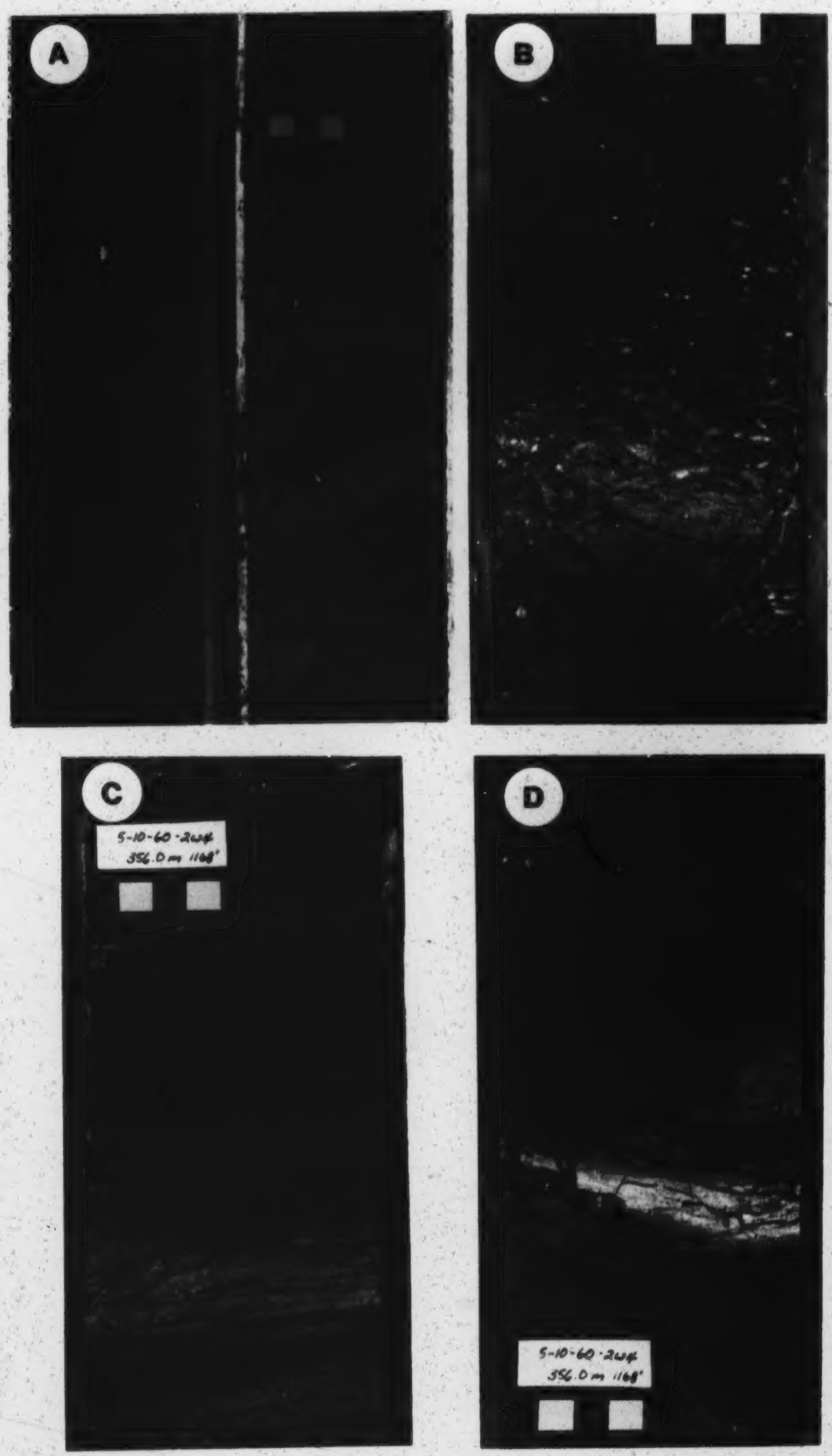
Figure 2.3 Subfacies 1d

a) Carbonaceous mudstones with abundant thin coaly laminae and vertically orientated rootlets abruptly overlain by sideritic, laminated mudstones of subfacies 1c. The photograph is from the uppermost portion of the GR_3 lithosome, 12-13-62-4W4, 323 m. Scale bar gradations are in centimeters.

b) Laminated to massive carbonaceous mudstones. The photograph is from 14-12-62-2W4, 362 m (GR_4 lithosome). Scale bar gradations are in centimeters.

c) Thinly laminated carbonaceous mudstones interlayered with planar-laminated and small-scale cross-stratified sandstones. The photograph is from 5-10-60-2W4, 356 m (GR_5 lithosome). Scale bar gradations are in centimeters.

d) Continuation of Fig. 2.3c. massive carbonaceous mudstones. Note the relative increase in the organic content of the mudstone and the bleached appearance immediately below the upper contact of this bed. The photograph is from 5-10-60-2W4, 356 m (GR_5 lithosome). Scale bar gradations are in centimeters.


A
B
C
5-10-60-2w4
356.0m 1168'
D
5-10-60-2w4
356.0m 1168'

increasingly massive, mottled and root-penetrated towards the top of the bed (Fig. 2.3 a,b and c). Vertically-orientated rootlets up to 15 cm in length have been observed near the top of beds, but rootlets on the order of 2 to 5 cm are more typical (Fig. 2.3a). Commonly the carbonaceous mudstones are sideritized. Small (1 cm) subrounded sideritized mudstone clasts have been occasionally observed. Rare thin (0.2-6.0 cm) very fine-grained sandstones and siltstone beds are interbedded with the carbonaceous mudstones. Recognized sedimentary structures within the sandstone beds include planar-laminations and low amplitude, rounded, asymmetrical ripples (Fig. 2.3c). Biogenic sedimentary structures were not observed; however, as previously mentioned, mottled textures are common near the top of the bed.

Interpretations:

Beds of subfacies 1d are interpreted to indicate the establishment of emergent conditions and the development of peat-forming swamps or marshes. The majority of modern coastal peat deposits accumulate in marsh or swamp areas in the interdistributary areas of upper and lower delta plains or in estuarine or lagoonal areas associated with barrier island systems. Peat deposits may also be associated with abandoned channels, particularly within lower delta plains settings, where organic debris is abundant (Baganz 1975 *et al.*, Horne *et al.*, 1978). The thinly-laminated carbonaceous mudstones, which typically occur near the base of beds, are interpreted to represent the suspension settling of organic-rich muds in a low energy environment. The interbeds of of planar-laminated and small-scale cross-stratified sandstones and siltstones represent rare times when clastic material was introduced into the swamp or marsh area. The presence of planar-laminations and low-amplitude wave ripples within these beds is indicative of moderate- to high-energy wave reworking and implies a proximity to the shoreline. However, with the exception of these infrequent beds, the swamp or marsh vegetation acted as a sediment filter, allowing only occasional layers of coarse clastic material to settle. Upwards, the mudstone beds become mottled, very carbonaceous, micaceous and contain vertically-oriented rootlets suggesting the development of a seat earth and peat horizon. The localized, light to bleached colour of the carbonaceous mudstones is interpreted to be indicative of reducing conditions associated with the decomposition of organic material. The thickness of these horizons (0.3 to 1.8 m) and the argillaceous nature of this subfacies reflects the development of immature soil horizons in a rapidly subsiding setting. High rates of subsidence would allow fine-grained clastics to mix with decaying vegetation; however, the vegetation restricted coarse clastic influx. Abundant carbonaceous material and siderite, as suggested for subfacies 1c, is considered to reflect organic-rich mud accumulation within an oxygen-restricted brackish water setting. Oxygen and salinity stresses are interpreted to have been more extreme during deposition of subfaices 1d and account for the distinct absence of biogenic sedimentary structures.

2.2.6 Facies 2 - Bioturbated Sandstone

Description:

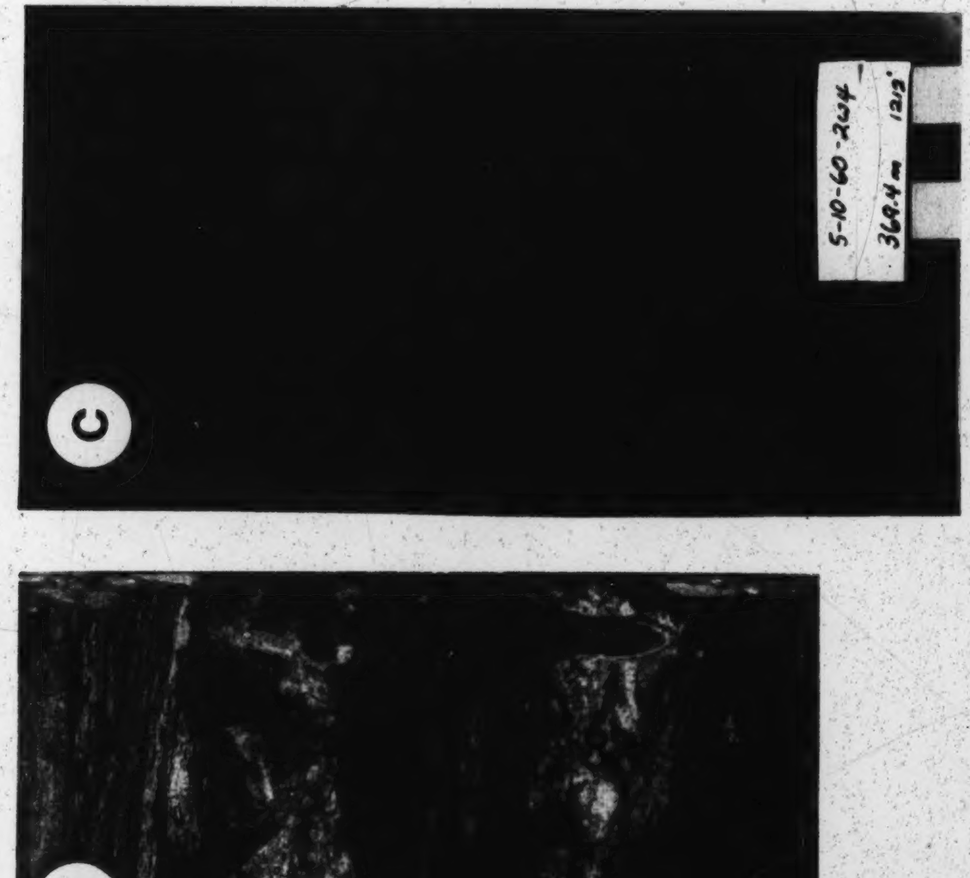
Facies 2 consists of fine- to medium-grained, thoroughly bioturbated, argillaceous sandstones (Fig. 2.4). Recognized ichnofossils include *Asterosoma*, *Cylindrichnus*, *Gyrolithes*, *Palaeophycus*, *Planolites*, *Skolithos*, and *Rosselia*. Locally, the intensity of bioturbation may be such that distinct ichnofossils cannot be recognized, only a bioturbate texture. Some relict lamination, cross-stratification and sandstone-mudstone intercalations are discernable, however the dominant feature is that of thorough biogenic reworking which results in a mottled, bioturbate texture. Mudstone, which may volumetrically account for up to 25% of the facies, occurs as discontinuous mud drapes, flasers and laminae. The basal and upper contacts of this facies are typically gradational and burrowed, however, the degree of bioturbation commonly obscures the recognition of the exact character of the basal contact.

Figure 2.4 Facies 2

a) Thoroughly bioturbated sandstones characterized by a high density, monospecific ichnofossil assemblage of *Gyrolithes* (GY). Some relict planar lamination is recognizable in the upper portion of the photograph; however the dominant feature is that of thorough biogenic reworking. The photograph is from 7-1-62-2W4, 319 m (GR_5 lithosome). Scale bar gradations are in centimeters.

b) Thoroughly bioturbated, water-saturated sandstone. A *Conichnus* (CO) burrow is present in the center, right portion of the photograph. Other recognized ichnofossils include *Palaeophycus* and *Skolithos*. The photograph is from 14C-27-60-3W4, 411 m (GR_1 lithosome). Scale bar is 5 cm.

c) Small-scale cross-stratified sandstone (Facies 3) grading upwards into a carbonaceous, bioturbated sandstone. The bioturbated sandstone is characterized by ichnofossil assemblages dominated by *Skolitos*. The photograph is from 5-10-60-2W4, 370 m (GR_5 lithosome). Scale gradations are in centimeters.


C
5-10-60-204
369.4 m 1212'
B
A

Interpretations:

Beds of facies 2 are characterized by the enhanced preservation of biogenic sedimentary structures relative to physical sedimentary structures. This preservational bias reflects thorough biogenic reworking of the substrate, resulting in the variable to complete destruction of primary physical sedimentary structures. Such thorough biogenic reworking is interpreted to be a reflection of optimal physical and biological conditions for benthic colonization.

The high diversity ichnofossil assemblages which characterize this facies reflect optimal ecological conditions associated with a stable, predictable environmental setting. Environmental conditions such as salinity, nutrient availability, oxygenation and substrate consistency, as indicated by the diversity of ichnofossils, are interpreted to have been optimal for the development of a stable benthic community of both suspension- and deposit-feeding organisms. Such optimal physical and chemical conditions are typically associated with deposition within an environmentally stable, shallow open marine or shelf setting. The paleoenvironmental significance of the ichnofossil assemblages which characterize this facies will be discussed in more detail in chapter 3.

Although most physical sedimentary structures have been destroyed because of biogenic reworking, the lithology and relict lamination or cross-stratification implies that currents and waves were, at times, of sufficient intensity to cause tractional transport of fine- to medium-grained sand. This suggests that sediment transport was restricted to episodic, short durtion events such as storms or, alternatively, lower-intensity intervals of more continuous sediment transport. In the first case, the record of biogenic reworking reflects the activities of an opportunistic benthic population rapidly inhabiting and exploiting the event beds. In the second scenario, an equilibrium population inhabits a relatively stable, predictable setting. In either case, the intense bioturbation precludes the interpretion of the paleohydrodynamic conditions of the depositional environment.

2.2.7 Facies 3 - Small-scale Cross-stratified Sandstones

Description:

Facies 3 is characterized by very fine- to fine-grained, small-scale (< 4 cm set thickness) cross-stratified sandstones (Fig. 2.5). Sets of small-scale cross-strata are arranged in 1 to 15 cm thick cosets. Individual cross-laminae are differentiated by slight variations in grain size and the degree of cementation, which result in differential bitumen saturations. The geometry and internal stratification which characterizes these sandstones is variable and complex. Both tabular- and trough-shaped sets are common, with the latter being dominant. Tabular-shaped sets typically display asymmetrical form-sets and internally, form-discordant, steeply dipping (angle-of-repose) cross-stratification. The lower bounding surfaces are flat and planar, but may be inclined up to an angle of 10°. In contrast, the nature of the upper bounding surfaces are much more variable, and may be undulatqry, scoured or planar. The trough-shaped sets are characterized by slightly asymmetrical form-sets and internally, form-discordant, low angle (5 to 15°) cross-stratification. Rarely the trough-shaped sets exhibit angular to rounded, symmetrical form-sets with form-concordant symmetrical, "chevron-like" cross-stratification. The lower bounding surfaces of the trough-shaped sets are generally sharp, undulatory or scoured. The upper bounding surfaces are either sharp and flat, scoured or conformable with the overlying form-set.

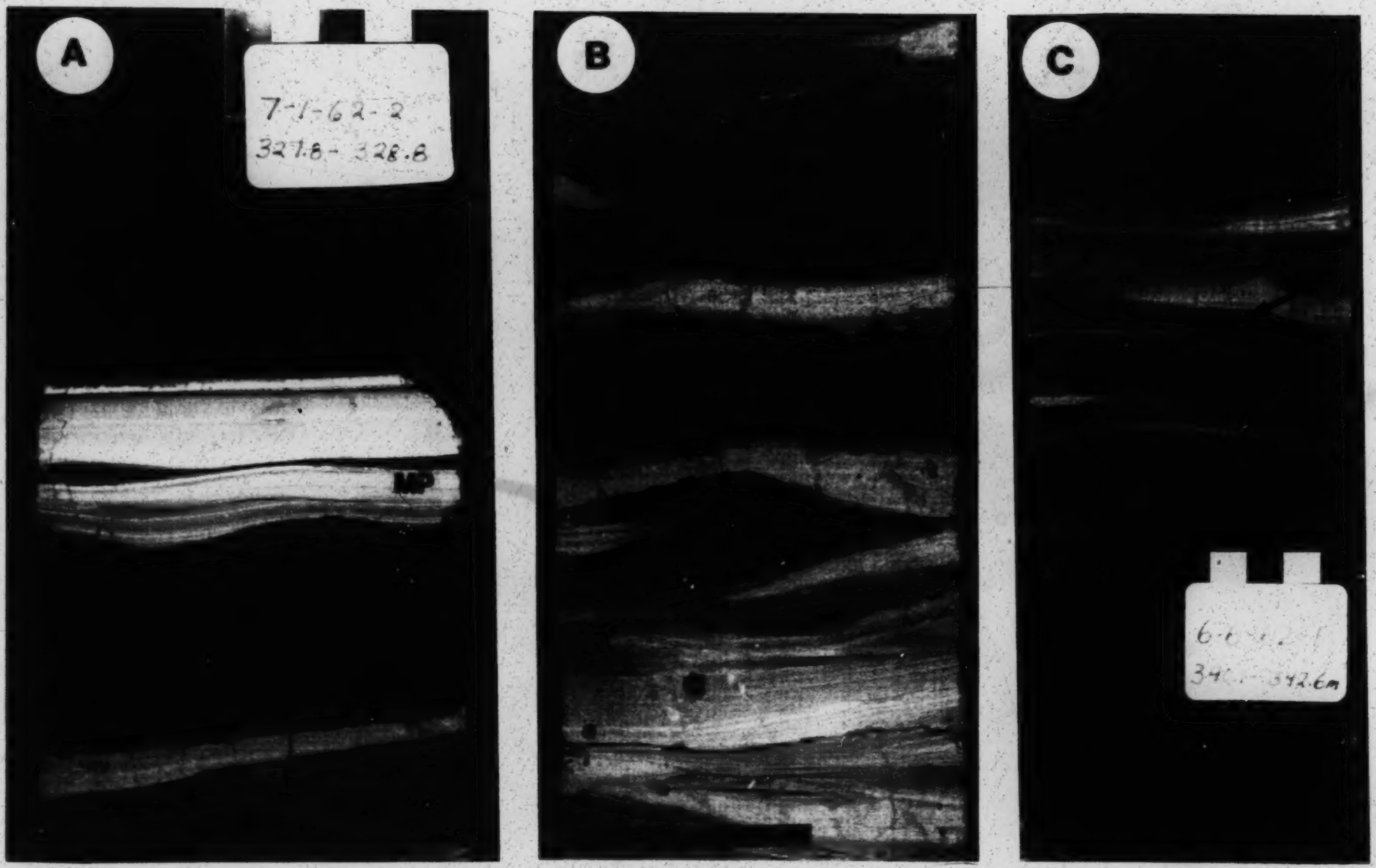
Thin (1 to 6 mm) mudstone drapes (Fig. 2.5c) and thicker (2 to 5 cm) partings (Fig. 2.5 a and c) are a common feature of this facies. The mudstone drapes and partings separate sets or cosets of small-scale cross-stratified sandstone and also separate cosets of small-scale cross-stratification from cosets of large-scale cross-stratification and planar-lamination. Paired mudstone drapes or "couplets" (cf. Boersma, 1969) are infrequent; where encountered they consist of two thin (0.5 to 3 mm) mudstone drapes separated by a thin (< 3 mm) sandstone lamina (Fig. 2.5c). Similarly, most of the mudstone partings

Figure 2.5 Facies 3

a) Fine-grained, small-scale cross-stratified sandstones with low amplitude, rounded profile ripple form-sets. Note the mudstone parting (MP) conformably overlying the ripple form-sets.The small-scale cross-stratified sandstones are overlain by planar-laminated sandstones (PL). The photograph from 7-1-62-2W4, 327.8-328.8 m (GR_5 lithosome). Scale bar gradations are in centimeters.

b) Fine-grained, small-scale cross-stratified sandstones with burrowed bed tops and mudstone partings and drapes. Note the small *Skolithos* burrows (SK) which penetrate the upper portions of the sandstone beds. The photograph 6-6-62-1W4, 337.5-338.2 m (GR_5 lithosome). Scale bar is 5 cm.

c) Fine-grained, small-scale cross-stratified sandstones with thin carbonaceous mudstone drapes (MD) mantling ripple form sets. The photograph is from 6-6-62-1W4, 341 m (GR_5 lithosome). Scale bar gradations are in centimeters.


A
7-1-62-2
327.8-328.8
MP
B
C
6-6-[illegible]-1
34[illegible]-342.6m

consist of thin (< 4 mm) mudstone drapes separated by very thin (< 2 mm) sandstone laminae. The lower contacts of the mudstone drapes and partings are typically sharp, but conformable with the underlying form-sets. The upper contacts are generally sharp, planar or scoured. The mudstone drapes and partings occur in a regular manner, typically increasing in abundance upwards within beds.

The relative degree of bioturbation within the small-scale cross-stratified sandstones is typically low and is characterized by low density and low diversity ichnofossil assemblages dominated by *Skolithos*, fugichnia, and minor *Rosselia*, *Cylindrichnus*, *Gyrolithes*, *Palaeophycus* and *Planolites* (Fig. 2.5c). Locally, the relative degree of bioturbation can be intense, particularly in thicker mudstone partings.

Interpretations:

The internal stratification which characterizes this facies is interpreted to be a product of the migration of small-scale current, wave and combined flow ripples. The tabular-shaped sets with their characteristic steep, asymmetrical form-set profiles and angle-of-repose cross-stratification are interpreted to represent current ripples. Unidirectional flow sediment transport experiments have shown that in very fine- to fine-grained sands current ripples are stable between current velocities of 15 and 60 cm/s (Middleton and Southard, 1984). The two types of trough-shaped sets are interpreted to be a product of waves. The trough-shaped sets with symmetrical form-sets and internal, form-concordant cross-stratification are interpreted to represent oscillation wave ripples. The other type of trough-shaped small-scale cross-stratification, characterized by slightly asymmetrical form-sets with low angle, form-discordant cross-strata, is interpreted to be a product of migrating wave ripples.The predominance of this type of small-scale cross-stratification over all other forms reflects the predominance of combined flow conditions in shallow marine and marginal marine settings (*cf.* Arnott and Southard, 1990).

The abundant mudstone drapes and thicker partings which are separate sets or cosets of small-scale cross-strata are interpreted to reflect regular fluctuations or reductions of flow velocity. During these periods of reduced flow velocity thin mud layers were deposited from suspension. Such flow velocity fluctuations may be related to episodic events such as storms or floods, or more regular events associated wide tidal currents. The regular and repetitive manner in which mudstone drapes and partings occur within the cross-stratified sandstones is interpreted to reflect regular patterns of current velocity unsteadiness which are interpreted to be associated with a tidal currents. Tidally-influenced environments are characterized by several scales of current velocity unsteadiness, of which the most important are: (1) fluctuations in flow velocity and depth within the daily diurnal of semidiurnal tidal cycle; (2) flow velocity, depth and direction fluctuations during the fortnightly spring-neap cycle; and (3) fluctuations over the equinoctial or seasonal cycle (Elliot and Gardiner, 1981).

The thin, sometimes paired, mudstone drapes may record patterns of current unsteadiness associated with the daily ebb-flood cycle. During a daily tidal cycle tractional sediment transport is restricted to short-duration periods in which the ebb and/or flood current velocities are above the critical threshold for sediment transport. During the daily slack water periods, current velocity is significantly reduced and suspended sediment settles out of suspension. Therefore, in theory, a complete semidiurnal daily cycle will produce a "couplet" (*cf.* Visser, 1980) which consists of a bed or lamina of cross-stratified sand bound above and below by a reactivation surface or pause-plane which may be overlain by mud drapes. Each mud layer represents the deposits of a single slack water period and the sand layer records active tractional transport between the two slack water periods. Deposition and preservation of the mud layer as a mudstone flaser or drape is dependent upon the volume of mud deposited, the degree of consolidation and the amount of scouring during the the next tractional transport period (Allen, 1982). The logistics of depositing and preserving a mud layer several millimeters or centimeters thick has been addressed by several investigators (Reineck and Wunderlich, 1968; Terwindt and Breusers, 1968, 1972; Hawley, 1981). The majority of the investigators agree that only a very thin (< 3 mm) mud layer could be the product of a single slack water period and that the preservation potential of such a layer would be low. Therefore, the majority of the mudstone drapes, and essentially all of the partings appear to be related to longer-term periods of current unsteadiness. Theses patterns of current velocity unsteadiness are interpreted to have occurred over the spring-neap or seasonal scale.

In a typical fortnightly spring-neap tidal cycle, during spring tides peak ebb and flood current velocities reach their respective maximums. During these energetic periods the concentration of suspended sediment is high; however, any mud deposit during the daily slack water periods is easily eroded. As the fortnightly cycle progresses towards the neap, ebb and flood current velocities decrease, the concentration of suspended sediment decreases and the preservation potential of mud drapes deposited during the slacks increases. During neap tides tractional transport is significantly reduced, and may cease entirely (Terwindt and Breusers, 1972; Hawley, 1981). Therefore, during neap tides, slack water mud deposition is at a maximum and the preservation potential of the mud layers is also at a maximum. The thicker mudstone partings are indicative of prolonged periods of mud deposition and negligible sediment transport which are interpreted to be associated with seasonal patterns of current unsteadiness.

In many tidally-influenced environments, the winter months are characterized by frequent storms resulting in significant tractional transport, high concentrations of suspended sediment and a very low preservation potential for any mud deposited during periods of reduced current velocity. In contrast, during the summer months current energy levels are reduced, tractional sediment transport is reduced, or ceases, and the deposition and preservation potential of mud increases. In summary, the regular occurrence of mudstone drapes and partings within the small-scale cross-stratified sandstones suggests that several scales of current velocity, interpreted to be associated with tidal currents, were in operation during the deposition of this facies. The thickness of the majority of the mudstone drapes and partings suggests that these current velocity fluctuations were associated with fluctuations on the spring-neap or seasonal scale.

The small-scale cross-stratified sandstones are characterized by low density, low diversity ichnofossil assemblages dominated by *Skolithos*, fugichnia, and more rare examples of *Rosselia*, *Cylindrichnus*, *Gyrolithes* and *Palaeophycus*. Such assemblages are dominated by vertically-orientated dwelling and dwelling-feeding structures (*Skolithos*, *Rosselia*, *Cylindrichnus*, *Gyrolithes*) and are interpreted to be indicative of a moderately high energy environment. These energy conditions, combined with a shifting, particulate substrate, selectively exclude deposit feeding organisms. The low diversity and low density of ichnofossils is interpreted to reflect brackish water conditions. The paleoecological significance of the ichnofossil assemblages observed within this facies will be discussed in detail in Chapter 3

3.2.8 Facies 4 - Large-scale Cross-stratified Sandstones

Description:

Facies 4 comprises large-scale (> 4 cm) sets of planar-tabular and trough cross-stratified fine- to lower coarse-grained sandstone (Fig. 2.6). Set thickness ranges from approximately 8 cm to in excess of 75 cm. A definite value cannot be placed on the upper limit of set thickness values because of the segmented nature of the cores. Similarly, set thickness values could not be estimated. Individual cross-laminae, differentiated by colour and grain size differences, average 1 cm in thickness and typically display normal grading. The planar-tabular sets are characterized by parallel-dipping, planar to concave-upwards foresets which are inclined at angles ranging from 5 to 28° and intersect the lower bounding surface in an angular or slightly tangential manner. Typically, the trough-shaped sets are characterized by concave-upwards foresets which fan upwards into steeper inclinations and tangential and scoured basal contacts. Owing to the limited three-dimensional view provided by drill core and the size of the large-scale cross-strata, trough- and planar-tabular-shaped sets could not always be differentiated.

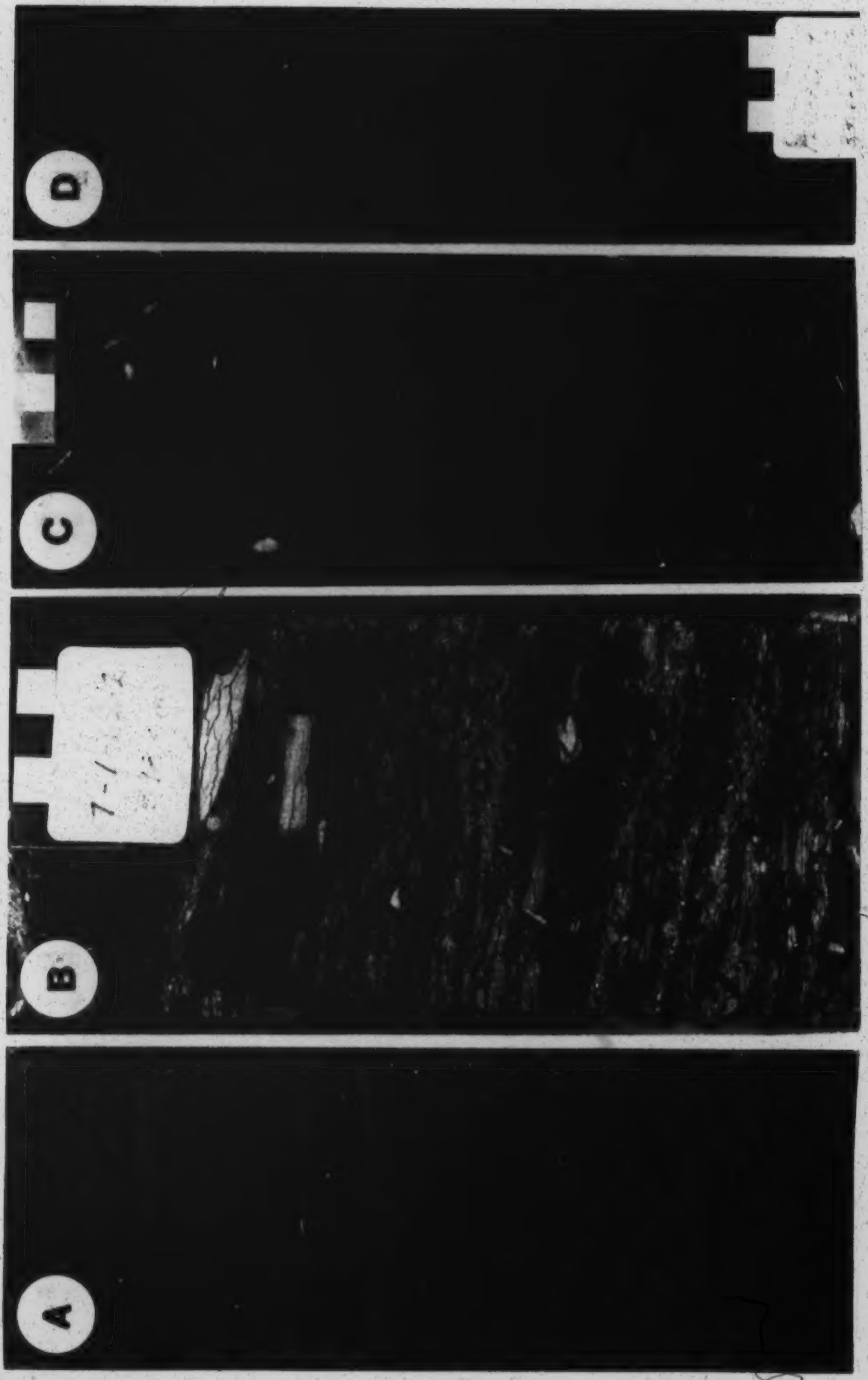
Figure 2.6 Facies 4

a) Fine-grained sandstones in which planar-laminations (PL) grade upwards into large-scale trough cross-stratified (LC) and small-scale cross-stratified sets. The photograph is from 6-6-62-1W4, 366 m (GR_3 lithosome). The scale bar is 5 cm.

b) Medium-grained large-scale cross-stratified sandstones. Note the poorly sorted nature of the sandstones and the abundance of small rounded siderite (S) and coaly mudstone clasts (CC) concentrated along bedding planes. The photograph is from 7-1-62-2W4, 398 m (GR_1 lithosome). Scale bar gradations are in centimeters.

c) Medium-grained, high-angle, large-scale trough cross-stratified sandstones. Some small rounded sideritic mudstone clasts are apparent in the lower portion of the photo. The photograph is from 10-15-61-1W4, 347 m (GR_6 lithosome). Scale bar gradations are in centimeters.

d) Fine-grained large-scale trough cross-stratified sandstones. Trough cross-stratification (TR) predominates in the upper portion of the photo whereas planar tabular (PT) cross-stratification predominates in the lower portion. Note the scoured bed contacts and small-scale cross strata overlying large-scale cross-stratified beds. The photograph is from 12-13-62-4W4, 333 m (GR_6 lithosome). Scale bar gradations are in centimeters.


A
B
C
D

Internally, within a large proportion of the large-scale cross-stratified sandstone beds, repetitive fining-upwards stratification sequences are common. A typical stratification, in ascending order, consists of large-scale cross-stratified sandstones, which are gradationally overlain by small scale cross-stratified sandstone, which are, in turn, abruptly overlain by mudstone drapes or partings. The mudstone drapes are characteristically thin (3 to 10 mm) and consist of thin laminations of mudstone, carbonaceous debris and sandstone. Thicker (1 to 4 cm) partings consist of intercalated mudstone and thin sandstone laminae and lenses. In some case multiple drapes or partings may be intercalated with thin (1 to 5 cm) small-scale cross-stratified sandstone beds, forming a thick heterolithic unit. The mudstone drapes and partings typically have sharp basal contacts that are conformable with the underlying small-scale cross-stratified form-sets and upper contacts which are sharp, typically scoured, but occasionally planar or bioturbated. Typically, the mudstone drape or parting is abruptly overlain by large-scale cross-stratified sandstone. Although, rarely a thin unit of small-scale cross-stratified sandstone can abruptly overlie the mudstone drape or parting. This small-scale cross-stratified sandstone is, in turn, abruptly overlain by large-scale cross-stratified sandstones.

Commonly, sets of large-scale cross-stratified sandstone may contain abundant rounded to angular mudstone intraclasts. The intraclasts are composed of poorly laminated mudstone or siderite-cemented mudstone and range in size from 0.2 cm to in excess of 7.5 cm (width of drill core). They typically occur as isolated randomly oriented intraclasts, concentrated zones at the base of bedding units or, less commonly, as distinct zones or layers which are preferentially aligned along foreset laminations. Locally intraclasts may comprise up to 50% of a bed.

Biogenic sedimentary structures are typically rare within this facies, however some very low density, low diversity assemblages comprised exclusively of *Skolithos*, *Planolites* and Fugichnia have been observed. While the relative degree of bioturbation is typically low in the cross-stratified sands, the mudstone drapes and partings found within the cross-stratified sandstones may be intensely bioturbated. The ichnofaunal assemblages observed within the partings and drapes are similar to those observed within the sandstones themselves except that *Planolites* is dominant over all other forms.

Interpretations:

Beds of this facies are interpreted to be a product of migrating straight-crested and linguoid dunes influenced by relatively strong asymmetrical oscillatory (combined flow) flows produced by shoaling waves or unidirectional currents generated by fluvial or tidal currents. Dunes are lower flow regime, flow-transverse bed forms that are similar to small ripples in geometry and kinematics, but differ by an order of magnitude in spacing and amplitude (Middleton and Southard, 1984). In sediment sizes with mean diameters greater than 0.2 mm dunes are typically stable at moderate energy flow conditions between those in which small-scale ripples are the stable bedform and those in which plane beds are the stable bedform. Experimental studies have indicated that for grain sizes similar to those observed within Facies 4, dunes are the stable bedforms between flow velocities of 40 cm/s and 100 cm/s (Middleton and Southard, 1984). The planar-tabular sets with parallel-dipping, planar foresets are interpreted to reflect bedload transport of sand in migrating straight-crested (2-dimensional) dunes or bars.The trough-shaped sets with fanning-upwards, concave-upwards foresets are interpreted to record tractional sediment transport in migrating linguoid (3-dimensional) dunes. The ubiquitous nature of cross-stratification precludes any detailed paleoenvironmental interpretations soley based in the occurrence of this stratification type. However, a number of accessory features within this facies provide insights as to the nature of the depositional setting.

The repetitive fining-upwards lithostratification cycles with their associated mudstone drapes and partings suggest that flow conditions were characterized by regular, periodic fluctuations in current velocity. Each fining-upwards lithostratification cycle, despite showing considerable variability, records the waning or progressive decrease of current velocities. In an overall, generalized sequence, the large-scale cross-stratified sandstones reflect energetic flow conditions in which large-scale bedforms (dunes) were active. The overlying small-scale cross-stratified sandstones represent intermediate conditions in which large-scale bedforms were not acitve, but during which sediment was actively transported in small-scale bedforms (ripples). Mudstone drapes and partings mantling the form-sets of the small-scale cross-stratified sandstones reflect periods of reduced current velocity in which mud was deposited from suspension and tractional transport of sand was negligible, or nonexistent. The thickness of the mudstone drapes and partings clearly indicates that they are not products of single slack tides, but rather, they have accumulated over several successive slack water periods (*cf.* Terwindt and Breusers, 1972; Hawley, 1981). Similarly, the presence of biogenic sedimentary structures within the mudstone partings, and particularly the mudstone drapes, implies that periods of reduced sediment transport were of sufficient duration to facilitate colonization of the substrate by benthic organisms.

The small-scale stratification cycles are interpreted to reflect current velocities fluctuations associated with tidal currents. However, it is not clear if the scale of current velocity unsteadiness occurs over a seasonal scale or over the shorter-duration, fortnightly spring-neap tidal cycle. The fact that the stratification cycles preserve only waning flow sequences (*i.e.* evidence of progressively waxing flow conditions was not observed), may favour seasonal-scale patterns of current velocity unsteadiness. Despite the uncertainty of which scale of current unsteadiness the cycles represent; the repetition of the cycles implies a degree of regularity. It is this degree of regularity which is suggestive of a tidally-influenced depositional setting.

The general absence of preserved ichnofossils within this facies suggests that the depositional environment may have been for the most part inhospitable to benthic organisms. High current velocities capable of transporting medium-grained sands in migrating large-scale bed forms may have selectively excluded the majority of benthic species from this depositional environment. Alternatively, the energetic nature of the depositional environment may have significantly reduced the preservation potential of biogenic sedimentary structures. The low diversity and density of ichnofossils is also interpreted to reflect stressful environmental conditions associated with a brackish water depositional setting. Detailed paleoenvironmental implications of the ichnofossil assemblages observed within facies 4 will be discussed within Chapter 3.

2.2.9 Facies 5 - Planar-laminated to Low-angle Cross-stratified Sandstone

Description:

Facies 5 is characterized by coarse- to fine-grained, low-angle (< 5°) cross-stratified or planar-laminated sandstones. The majority of the planar-laminated beds lie in the fine- to lower medium-grained size range. Planar-laminated beds range from thinly laminated to thinly bedded (*cf.* Ingram, 1954). Individual laminae vary in thickness from 1 to 10 mm and tend to be normally graded. Thicker (1 to 3 cm) beds may be inversely graded; however, generally they are normally graded. Typically, laminae and beds are arranged into planar-tabular sets (Fig. 2.7), but, somewhat subtle, wedge-shaped sets of oppositely-dipping laminae are common. Planar and scoured truncation surfaces are also common.

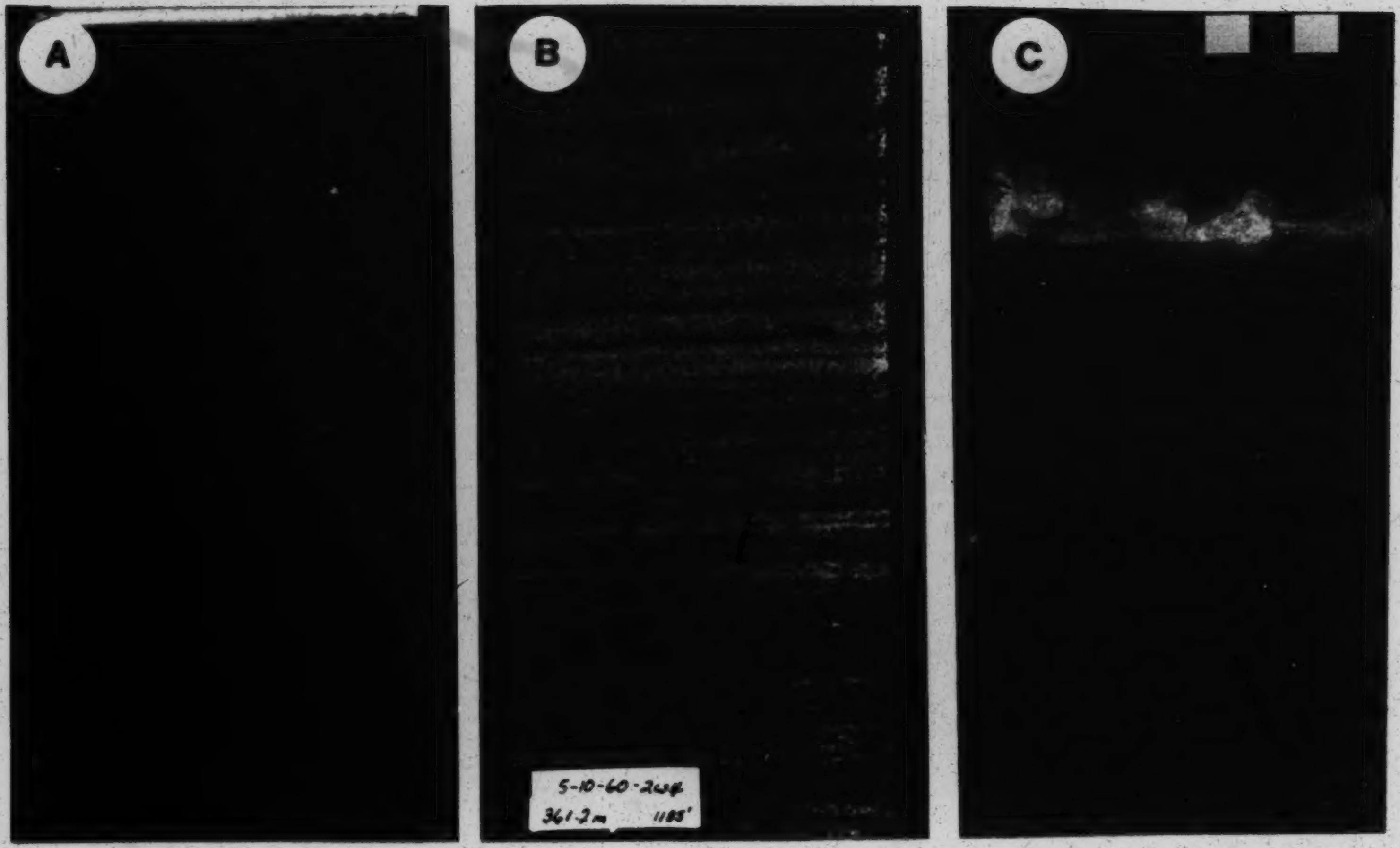
Carbonaceous material is common as discontinuous to continuous laminae and concentrated along bedding planes (Fig. 2.7b). Angular mudstone intraclasts, 0.5 to 7.5 cm in width are common, particularly in the low-angle cross-stratified beds, but generally absent in the planar-laminated beds. Biogenic sedimentary structures are typically not observed within beds of this facies. However, in the upper portions of the Grand Rapids Formation; in particular the GR_5 lithosome, the sandstones may be characterized by horizons that are pervasively bioturbated with monotypic to low diversity ichnofossil assemblages dominated by *Gyrolithes*.

Figure 2.7 Facies 5

a) Fine-grained planar-laminated sandstones. Note the even, parallel nature of the lamination with only minor discordances in the upper portion of the photograph. The photogaph is from 7-1-62-2W4, 327 m (GR$_5$ lithosome). The scale bar is 5 cm.

b) Medium-grained planar-laminated sandstones with abundant carbonaceous debris concentrated along bedding planes. The photogaph is from 5-10-60-2W4, 361 m (GR$_5$ lithosome). Scale bar gradations are in centimeters.

c) Fine-grained planar-laminated sandstones with thin caps of small-scale cross-stratification. The photogaph is from 7-1-62-2W4, 325 m (GR$_5$ lithosome). Scale bar gradations are in centimeters.



5-10-60-2w4
361.2m 1185'

Interpretations:

The planar-laminated sandstones of Facies 5 are interpreted to reflect the sediment transport and deposition under upper flow regime conditions. In very fine-grained sediments (silt and very fine-grained sand), planar laminations may develop in low energy settings is response to suspension fall-out without subsequent tractional transport. Sediments deposited from suspension will conform to the depositional surfaces, and due to differential grain size settling, will produce planar laminations. However, the grain size distribution is Facies 5 ranges from fine- to coarse-grained, indicating that a suspension deposition origin is not possible. In coarse sediments (> 0.7 mm) plane beds may be stable under both upper and lower flow regime conditions (Harms *et al.*, 1982; Middleton and Southard, 1984). This results in two possible, ambiguous interpretations for the origin of planar-laminations in coarse-grained sandstones. However, owing to the very narrow range of flow velocities over which lower flow regime plane beds are stable, significant accumulations of planar-laminated sandstones would not be expected to have a lower flow regime origin (Harms *et al.*, 1982). Furthermore, only a small percentage of the planar-laminated sandstones are coarse-grained suggesting that the majority, if not all, of the planar-laminated beds reflect upper flow regime plane bed conditions.

Angular mudstone intraclasts are common in beds of this facies. Their characteristic angular nature implies minimal transportation prior to deposition suggesting they may have been deposited during periods of reduced flow velocity. Mudstone intraclasts exposed to high velocity flows would expectedly be round and small, if preserved at all. Therefore, only the small, rounded siderite-cemented mudstone clasts could have been deposited under upper flow regime plane bed conditions. Instead, the majority of the mudstone intraclasts appear to have been deposited during periods of reduced flow velocity. Similarly, the thin carbonaceous laminae and small angular coal clasts are also suggestive of periods of reduced flow velocity in which the tractional transportation of sand ceased and fine-grained sediments were deposited from suspension. The high ratio of surface area to mass and the predicted low settling velocities of the coal clasts, would preclude deposition from suspension, except during periods of very low flow velocities.

The near absence of biogenic sedimentary structures is, for the most part, related to the high energy flow conditions necessary to develop upper flow regime plane bed conditions. However, the presence of localized horizons pervasively bioturbated with *Gyrolithes* indicates that flow conditions were, at times, reduced such that benthic organisms could colonize and rework the substrate. The monotypic nature of this ichnofossil assemblage is interpreted to indicate stressed environmental conditions associated with a brackish water setting. The paleoecological significance of this ichnofossil will be discussed in more detail in Chapter 3.

2.2.9 Facies 6 - Massive Sandstone

Description:

Facies 6 is represented by poorly sorted, fine- to coarse-grained massive sandstones (Fig.2.8 a-e). Grain size, although variable within this facies, remains relatively uniform within individual beds. The most characteristic feature of this facies is the distinct absence of any recognizable physical and biogenic sedimentary structures. A particularly common feature observed within beds of this facies is the occurrence of zones of concentrated, randomly orientated rounded to angular, sideritized mudstone intraclasts (Fig. 2.8 c-e). In some beds the intraclasts make up in excess of 70 % of the bed volume (Fig. 2.8 c). Intraclast size is extremely variable, ranging from a few millimeters to greater than the width of the drill core (6.5 to 8.0 cm). Biogenic sedimentary structures are not observed in the sandstones, however some of the mudstone intraclasts displayed similar ichnofossil assemblages as observed within subfacies 1c. Basal contacts of this facies are highly variable from gradational to sharp and scoured. Where the contact is sharp it is typically overlain by a layer of concentrated mudstone intraclasts.

Figure 2.8 Facies 6

a) Fine-grained massive sandstone interbedded with small-scale cross-stratified sandstone. The photograph 4-25-62-3W4, 356 m (GR_1 lithosome). Scale bar is 5 cm.

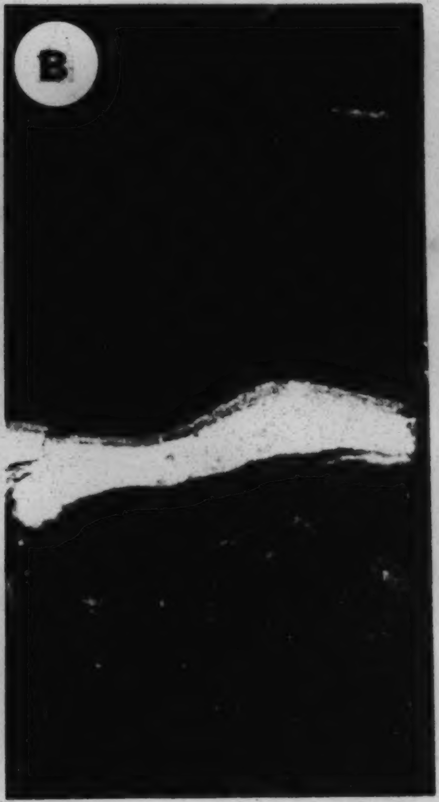
b) Fine-grained massive sandstone with a mudstone rip-up clast. The sandstone does not display any evidence of primary lamination or biogenic reworking. The photograph is from 3-6-63-3W4, 359 m (GR_1 lithosome). Scale bar is 5 cm.

c) Fine-grained massive sandstone with concentrated angular to subrounded mudstone intraclasts and rounded siderite-cemented mudstone clasts. The photograph is from 6-23-61-1W4, 330 m (GR_6 lithosome). Scale bar is 5 cm.

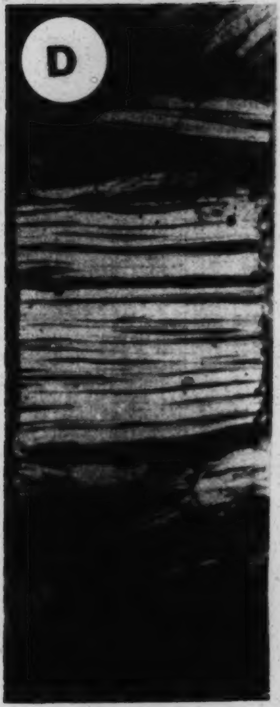
d) Fine-grained massive sandstone with large angular mudstone intraclasts. The photograph is from 10-22-61-1W4, 338 m (GR_6 lithosome). Scale bar is 5 cm.

e) Fine-grained massive sandstone with small subrounded to subangular mudstone intraclasts. The photograph is from 11-5-63-3W4, 364 m (GR_1 lithosome). Scale bar is 5 cm.

A


B

C


D

E

Interpretations:

The origin of the massive fabric which characterizes this facies is somewhat problematic, the absence of physical sedimentary structures may reflect depositional hydrodynamic conditions or the post-depositional destruction or modification . Three possible processes may explain the absence of sedimentary structures within this facies: (1) biogenic reworking; (2) liquefaction; or (3) initial deposition in a structureless state.

Physical sedimentary structures may be destroyed by intense biogenic reworking (Howard and Reineck, 1981; Ekdale *et al.*, 1984). If biogenic reworking was the process responsible for the generation of the massive texture observed within Facies 6, some remnants of biogenic structures would be expected to be preserved. Furthermore, if intense biogenic reworking was the process responsible, it would tend to produce a bioturbate texture rather than a massive texture.

Liquefaction or fluidization are two post-depositional processes that may obliterate sedimentary structures and impart a massive texture to sediments. Liquefaction is a process in which loosely packed, fine-grained sediments are temporarily supported in a fluid matrix (Collinson and Thompson, 1982; Allen, 1984). Liquefaction may occur in response to seismic induced shock, a build-up of pore fluid pressure in response to a rise in water level, or an episode of rapid sedimentation. Due to the inherent high primary porosity, low effective permeability and the volume of interstital water, liquefaction occurs primarily in fine-grained argillaceous sediments. Conversely, due to the high effective permeability and porosity, liquefaction is rare in sandstones. Fluidization involves the introduction of water from an external source into the pore spaces of a loosely packed, fine-grained sediment. If the injection of water is vigorous enough grains will be temporarily suspended. Typically, the relative movement of grains and fluid during fluidization result in preferential settling and sorting (Collinson and Thompson, 1982). Considering this, fluidized beds should display some evidence of normal grading. However, the massive beds are charateristically very poorly-sorted. Also, fluid escape structures, such as dish and pillar structures, were not observed. Furthermore, sandstones, because of their high permeabilities, will not be prone to fluidization. Therefore, primarily due to the high effective permeability of the massive sandstones, neither fluidization nor liquefaction provide a plausible mechanism to account for the massive texture of this facies, nor would either process be capable of supporting mudstone clasts similar to the size observed within Facies 6.

A third possible mechanism, which may account for the massive nature of these sandstones, is rapid deposition from suspension without subsequent tractional transport. Very energetic conditions such as those which characterize grain flows may produce hydrodynamic conditions capable of depositing large quantities of massive sand. Recently, Arnott and Hand (1989) conducted a number of flume experiments to determine how rapid sediment fallout might affect the development of bedforms, primary sedimentary structures and grain fabric. The results indicate that the formation of primary lamination can be suppressed and a massive fabric generated under upper flow regime plane bed conditions when aggradation is sufficiently rapid.

An upper flow regime origin for these massive beds is also supported by the common interbedding of massive and planar-laminated beds. The planar-laminated beds reflect upper flow regime conditions when the sediment fallout, and subsequently bed aggradation, were somewhat reduced allowing planar laminations to form. Arnott and Hand (1989) found that planar laminations developed readily at low rates of sediment fallout, but became less distinct at moderate rates and disappeared when the rate of bed aggradation exceeded 4 cm/min. These changes in the rate of sediment fallout and aggradation also explain why massive beds with zones of highly concentrated mudstone intraclasts are interbedded with planar-laminated beds which are devoid of mudstone intraclasts. High rates of bed aggradation which prevented the formation of planar-laminations allowed mud clasts to be rapidly buried before they were subjected to any significant erosion, despite being deposited under upper flow regime conditions. In contrast, mud clasts subjected to upper flow regime conditions capable of generated planar-laminations (i.e. lower sediment fallout rates and/or bed aggradation rates) would probably not survive the energetic conditions associated with high rates of tractional transport. Therefore, in conclusion, rapid suspension fallout combined with a high rate of bed aggradation represents the most plausible mechanism to explain the massive texture of this facies. High sediment fallout and aggradation rates also account for the presence of zones of concentrated mudstone intraclasts.

2.2.10 Facies 7 - Heterolithic Facies

Facies 7 consists of alternating, interbedded or intermixed layers of sandstone and mudstone. The mudstone beds are typically massive or poorly laminated and display evidence of biogenic reworking. Sandstone beds range in thickness from lenticles (0.5 to 1.0 cm) to thicker interbeds (up to 10 cm). Internally, they may be graded, cross-stratified or planar-laminated. Three subfacies are delineated on the basis of the scale of interbedding, internal structure and the relative degree of bioturbation.

2.2.11 Subfacies 7a - Intercalated sandstone and mudstone

Description:

Subfacies 7a comprises millimeter- to centimeter-scale alternations of laminated mudstone and very fine-grained sandstone (Fig. 2.9 a and b). The sandstone and mudstone beds are similar to the interlaminated mudstones of Subfacies 1b, are arranged into distinct, repetitive "couplets", often giving the facies a "varved-like" appearance. Sandstone beds range in thickness from 0.2 to 3 cm. The basal contacts of the sandstones beds are sharp, scoured and planar. Internally, the sandstone beds are typically massive and normally graded; however, thicker beds may be planar-laminated or small-scale cross-stratified (Fig. 2.9 c). Typically, the thicker (1 to 3 cm) sandstone beds are characterized by low-angle, tangential and, less commonly, steeply-dipping (angle-of-repose), small-scale

Figure 2.9 Facies 7

a) Thinly interbedded to intercalated sandstones and mudstones (Subfacies 7a). Thicker sandstone beds (up to 2 cm) are interbedded with mudstone and sandstone which are, in turn, interbedded on a millimeter scale. The photograph is from 12-13-62-4W4, 326.5 m (GR$_4$ lithosome). Scale bar gradations are in centimeters.

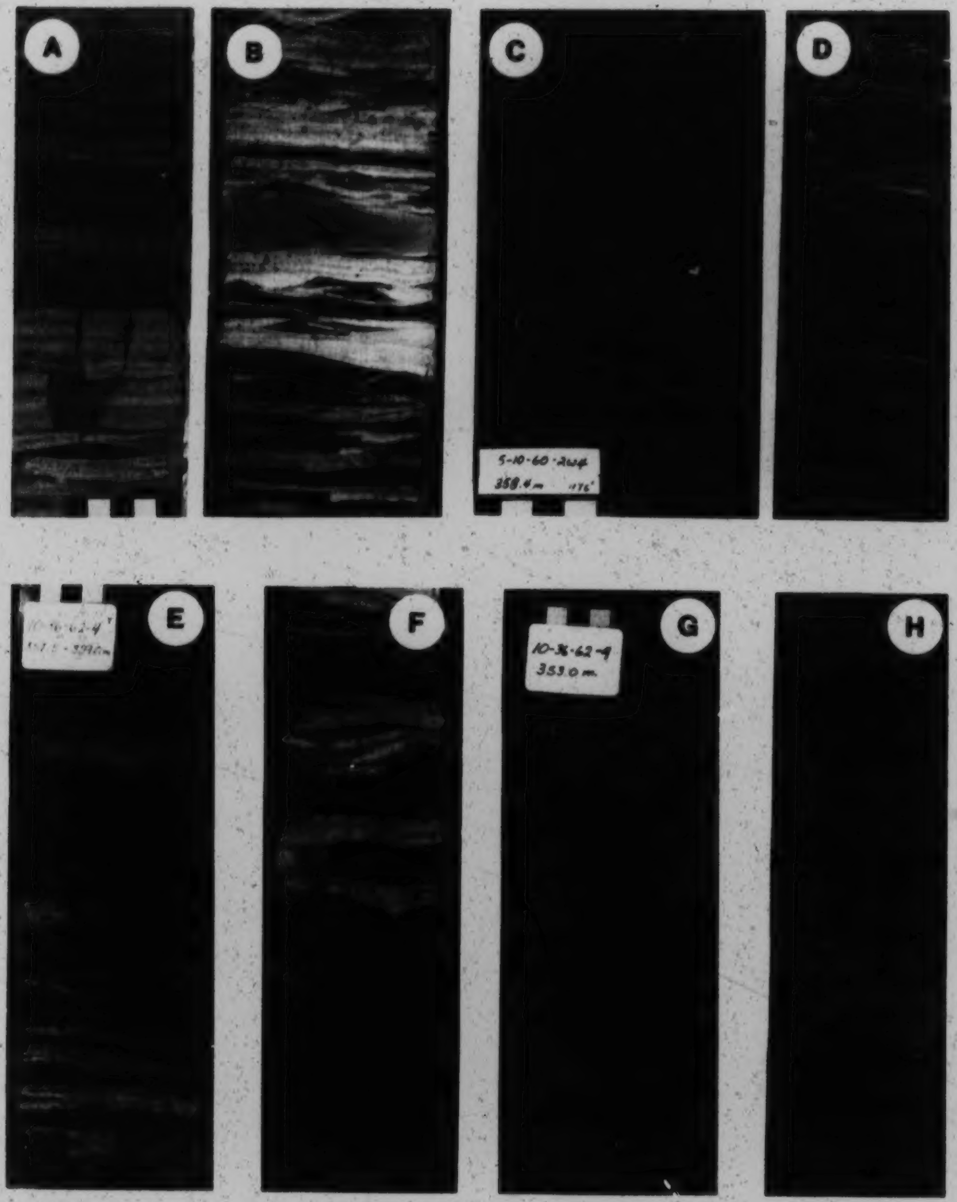
b) Thinly interbedded to intercalated sandstones and mudstones (Subfacies 7a) displaying lenticular bedding. Sandstone occurs as thin (< 1 cm) sandstone interbeds and lenses. The photograph is from 10-15-61-1W4, 373 m (GR$_4$ lithosome). Scale bar is 5 cm.

c) Interbedded small-scale cross-stratified sandstones and mudstones (Subfacies 7b). Note the abundance of syneresis cracks and the occurrence of isolated *Planolites* in the mudstone beds. The photograph is from 5-10-60-2W4, 358.4 m (GR$_5$ lithosome). Scale bar gradations are in centimeters.

d) Interbedded large-scale cross-stratified sandstones and mudstones (Subfacies 7b). The photograph is from 10-36-62-4W4, 355 m (GR$_1$ lithosome). Scale bar is 5 cm.

e) and f) Interbedded large-scale cross-stratified sandstones and mudstones (Subfacies 7b). Photographs are from 10-36-62-4W4, 357.5 to 359 m (GR$_5$ lithosome). Scale bar gradations in centimeters.

g) and h) Thoroughly biotubated, intermixed sandstone and mudstone (Subfacies 7c). The thorough degree of bioturbation which characterizes this subfacies obscures the recognition of any physical or biogenic sedimentary structures. Photographs are from 10-36-62-4W4, 353 to 354.5 m (GR$_4$ lithosome). Scale bar is 5cm.


A
B
C
5-10-60-2W4
358.4m 1176'
D
10-6-62-4
E
F
10-36-62-4
353.0m.
G
H

cross-stratification. Mudstone beds range in thickness from 0.4 to 4 cm. The basal contacts of the mudstone beds are sharp, flat or conformable with the underlying sandstone bed or, less typically, gradational. Internally, they are silty and thinly laminated (Figs. 2.9 a and b) or massive (Fig. 2.9 c). Although the thickness of interbeds is variable, the variation appears to be somewhat regular. Commonly, a bedding unit will possess sequences in which the mudstone beds will thicken upwards in each couplet and then thin-upwards. Concomitantly, the sandstone beds will thin- and thicken- upwards, however, bed thickness trends are not as readily apparent in the sandstone beds.

Soft sediment deformation structures are common and include: convolute laminations, ball-and-pillow structures, microfaulting, gas escape structures and rare flame structures. Although bedding units of this subfacies are typically flat bedded, some beds, particularly those that display evidence of soft sediment deformation, may be inclined at angles up to 30°. Syneresis cracks are abundant within the massive mudstone beds.

Bioturbation is extremely variable within this facies. Locally, it may be intense, resulting in the intermixing of sandstone and mudstone and the obliteration of primary stratification. In most cases, however, the laminated mudstones display only minor evidence of biogenic reworking, but, as the proportion of sandstone increases, the relative degree of bioturbation increases. Ichnologically, beds of this subfacies are characterized by low diversity, high density ichnofossil assemblages dominated by *Skolithos* and *Planolites*. Other associated ichnofossils include *Cylindrichnus*, *Rosselia* and *Palaeophycus*.

Interpretations:

The intercalation of sandstone and mudstone observed within Subfacies 7a implies the alternation of two depositional processes; the bedload transport of sand and the suspension-settling of mud. The generalized paleohydrodynamic interpretation, episodic deposition of sharp-based sand beds in an otherwise quiescent, mud-dominated, depositional setting, is very similar to that presented in the interpretations of Subfacies 1c. Internally, the low-angle, small-scale tangential cross-stratificatied sets reflect sediment transport influence by asymmetrical oscillatory waves. The increased proportion of sandstone and the increased average thickness of mudstone and sandstone beds is taken to imply that the physical events which resulted in the flow velocity fluctuations occurred more frequently, over a greater range of flow velocities and on a more regular basis during the deposition of Subfacies 7a.

The regular intercalation of sandstone and mudstone reflects regular periods of alternating higher- and lower- energy deposition. The physical process responsible for this inferred regular and repetitive alternation of current velocity is interpreted to be tidal currents. Tidal currents and their associated patterns of current velocity unsteadiness provide the most plausible mechanism to account for the rhythmic intercalation of sandstone and mudstone observed within subfacies 7a. The thickness of the mudstone layers (0.4 to 4 cm) suggests that the mudstone beds are not the products of single slack water periods, instead they are products of several successive tidal cycles (*cf.* Terwindt and Breusers, 1972; Terwindt, 1981; Hawley, 1981); however, the sandstones may represent single event-beds. Thus, the milimeter to centimeter thick intercalated beds of sandstone and mudstone which characterize subfacies 7a are interpreted to represent sediment deposition and accumulation over several successive tidal cycles. The thickening-upwards portions of the cycles reflect the progressive waning of current velocities, whereas, the thinning-upwards portion of the cycles reflects the progressive waxing of current velocities. This inferred progressive waning followed by progressive waxing of current velocities may be related to current velocity fluctuations over the fortnightly spring-neap tidal cycle, or longer-term, seasonal current velocity fluctuations. Although intercalated sandstones and mudstones similar to those observed within subfacies 7a have been reported from many modern and ancient non-tidal deposits, current velocity fluctations related to tidal currents provide the most plausible mechanism to account for the generation of cyclic intercalations of sandstone and mudstone (Terwindt, 1981; Terwindt and Breusers, 1972).

The soft sediment deformation structures observed within this subfacies primarily reflect the processes of liquefaction, slumping and sediment loading. These three processes occur preferentially in interbedded sediments which contain an appreciable proportion of argillaceous material and are characterized by high interstitial water volumes, and are interpreted to be indicative of rapid sedimentation rates.

The low density, low diversity ichnofossil assemblages dominated by *Planolites* and *Skolithos* combined with the presence of syneresis cracks are interpreted to indicate deposition within a brackish water setting that was subject to periodic salinity reductions. The paleoecological significance of the ichnofossil assemblages observed within this facies will be discussed in detail in Chapter 3.

2.2.12 Subfacies 7b - Interbedded sandstone and mudstone

Descriptions:

Subfacies 7b is the most common variation of the interbedded sandstone and mudstone facies encountered within the Grand Rapids Formation. It comprises interbedded laminated to massive mudstone and very fine- to fine-grained sandstone (Fig. 2.9 d,e and f). Basal contacts of this subfacies are gradational, and less commonly, sharp, flat or scoured. Sandstone interbeds range in thickness from 1 to 10 cm. Internally they are characterized by small-scale, asymmetrical wave cross-stratification and less commonly planar-laminations or low-angle, large-scale cross-stratification (Fig. 2.9 e). Many of the thicker (4 to 10 cm) sandstone interbeds display gradational sequences in which planar-laminated or low-angle, large-scale cross-stratified sandstones pass upwards into small-scale wave cross-stratified sandstone. The mudstones are massive to poorly-laminated and typically on the order of 0.5 to 2 cm thick. Internally, many of the mudstone beds consist of thin (2 to 8 mm) laminae or beds separated by thin laminae, beds or lenses of sandstone (Fig. 2.9 d and e).

Soft sediment deformation structures, similar to those observed within the interbedded mudstones and sandstones of subfacies 7a, are not common. Occasional microfaults and inclined beds (up to 20°) and rare contorted or convolute beds have been observed. Syneresis cracks are abundant in the massive mudstone beds.

The interbedded sandstones are characterized by low diversity, moderate density ichnofossil assemblages dominated by *Skolithos* and *Planolites*. The relative degree of bioturbation as variable but typically greater than that observed within Subfacies 7a. Typically, the thinly (1 to 3 cm) interbedded units display the highest degree of bioturbation, whereas, thickly (3 to 10 cm) interbedded units are weakly bioturbated to non-bioturbated.

Interpretations:

The interbedding of sandstone and mudstone in Subfacies 7b elicits a similar interpretation to Subfacies 7a; alternating periods of traction and suspension deposition, respectively. The increased thickness of the sandstone beds and the presence of large-scale cross-stratification and planar-lamination is suggestive of overall higher-energy depositional conditions. Within the sandstone interbeds, the gradational sequences in which low-angle, large-scale cross-stratification grades upwards into small-scale wave and combined flow ripple cross-stratification represent waning flow sequences, similar to those described in Facies 4, and record the progressive decrease of current velocities. As previously suggested, it is the repetitive manner in which these sequences occur that suggests that their origin is associated with tidal currents.

The regular and repetitive manner in which sandstone and mudstone beds are interbedded is suggested to reflect regular patterns of current velocity unsteadiness associated with deposition in a tidally-influenced setting. Several scales of current unsteadiness are inferred from Subfacies 7b.The thinnest (2-6 mm), sometimes paired, mudstone drapes may record patterns of current unsteadiness associated with the daily ebb-flood cycle. Each mudstone drape records suspension deposition during a single slack water period, while the intervening sandstone laminae record an interval of traction transport. However, as suggested in previous facies interpretations, the thickness and internal structure of the majority of mudstone beds suggests that their origin is a result of mud deposition over several successive slack water periods. Therefore, the interbedding of sandstone and mudstone in subfacies 7b may reflect patterns of current velocity unsteadiness over the seasonal scale or over the shorter-duration, fortnightly spring-neap tidal cycle.

The interpretation of relatively higher energy, shallower conditions or a more shoreward location, of Subfacies 7b relative to 7a, is also supported by the overall decrease in the intensity of bioturbation and the decrease in the density and diversity of ichnofossils. Fewer benthic species could tolerate the increased energy conditions.

2.2.13 Subfacies 7c - Mixed (homogenized) sandstone and mudstone

Description:

Subfacies 7c is characterized by mixed or homogenized mudstone and sandstone (Fig. 2.9 g and h). Subfacies 7c differs from Subfacies 7a and 7b in that distinct interbeds of sandstone and mudstone are not common; instead, Subfacies 7c is characterized by a bioturbate texture. Soft sediment deformation structures, particularly convolute bedding and ball-and-pillow structures, are common.

T,he relative degree of biogenic reworking is typically high within beds of this subfacies making ichnofossil identification very diffucult, virtually impossible in cases. Ichnofossil assemblages recognized within this subfacies are represented by the following forms: *Skolithos*, *Planolites*, *Cylindrichnus*, *Rosselia*, *Asterosoma*, *Gyrolithes* and *Palaeophycus*.

Interpretations:

The high relative intensity of bioturbation combined with the absence of any distinct physical or biogenic sedimentary structures precludes a detailed paleoenvironmental interpretation of this subfacies. However, the mixed sandstone and mudstone lithology of this subfacies, as with Subfacies 7a and 7b, suggests alternating periods of suspension deposition of mud and tractional transportation of sands. The thorough degree of biogenic reworking and intermixing of sandstone and mudstone which characterizes Subfacies 7c, compared to the interbedding and moderate bioturbation observed in Subfacies 7a and 7b, is suggestive of less stressful ecological conditions (*i.e.* salinity), or temporally, longer-term fluctuations in energy conditions (*e.g.* prolonged fairweather conditions) or, possibly, a combination of both. In either case, the benthic population thoroughly reworked the substrate intermixing sand and mud.

CHAPTER 3 ICHNOLOGY

3.1 Introduction

Historically, the Grand Rapids Formation has proven to be problematic to oil sands geologists with regards to biostratigraphy and paleoenvironmental interpretation owing to the paucity of body fossils. In contrast, ichnofossils are abundant, well preserved and represent extremely valuable tools which may be utilized in the interpretation of paleoenvironmental conditions. Ten ichnogenera have been recognized from the Grand Rapids Formation, these include: *Asterosoma, Bergaueria, Chondrites, Cylindrichnus, Gyrolithes, Helminthopsis, Macaronichnus, Monocraterion, Palaeophycus, Planolites, Rhizocorallium, Rosselia, Skolithos, Teichichnus* and *Zoophycos*. In addition to distinct ichnofossils, bioturbate textures, escape structures and nondescript, passively-filled shafts were recognized. Although somewhat problematic, each ichnogenera can be attributed to (1) a particular group (or groups) of organisms, (2) an ethological (or behavioural) category, and (3) a general trophic group (Table 3.1).

The predominance of ichnofossils compared to the paucity of body fossils is not a unique feature of the Grand Rapids Formation, but is a common characteristic of brackish water deposits reflecting the low preservation potential for body fossils in brackish water settings (Wightman *et al.*, 1987). Although body fossils can be potential sources of valuable paleoenvironmental and paleoecological information, ichnofossils are more readily preserved in such zones and may provide the only indications of the nature of the original biotic component of the depositional environment (Wightman *et al.*, 1987). Diagenetic factors which tend to have adverse effects on the preservation of body fossils commonly enhance the preservation and recognition of ichnofossils (Ekdale *et al.*, 1984; Frey and Pemberton, 1985; Wightman *et al.*, 1987). Another, often overlooked factor, is the nature of subsurface investigations. The size and limited three-dimensional view of the drill core may preclude the observation of body fossils particularly if their distribution is irregular. In contrast, ichnofossils, because of their size, abundance and preservation potential, tend to be more readily observed in drill core.

ICHNOFOSSIL	ETHOLOGICAL CLASSIFICATION	TROPHIC STRATEGY	PROBABLE ORGANISM
Asterosoma	Fodinichnia	Deposit-feeder	annelid
Bergaueria	Domichnia	Suspension-feeder	anemone
Chondrites	Fodinichnia	Deposit-feeder	sipunculid/annelid
Cylindrichnus	Domichnia/Fodinichnia	Deposit-feeder	annelid
Gyrolithes	Domichnia	Deposit-feeder	annelid
Helminthopsis	Fodinichnia	Deposit-feeder	annelid
Macaronichnus	Fodinichnia	Deposit-feeder	annelid
Monocraterion	Domichnia	Suspension-feeder	annelid
Palaeophycus	Domichnia	Carnivore	annelid
Planolites	Fodinichnia	Deposit-feeder	annelid
Rhizocorallium	Domichnia/Fodinichnia	Suspension-feeder	annelid
Rosselia	Fodinichnia	Deposit-feeder	annelid
Skolithos	Domichnia	Suspension-feeder	annelid
Teichichnus	Fodinichnia	Deposit-feeder	annelid
Zoopyhcos	Fodinichnia	Deposit-feeder	annelid

Table 3.1 Classification of ichnofossil from the Grand Rapids Formation.

3.2 RECURRING ICHNOFOSSIL ASSOCIATIONS

As previously eluded to, the overall distribution of ichnofossils within the sediments of the Grand Rapids Formation can be viewed in terms of eight distinct, recurring ichnofossil associations (Table 3.2). The concept of recurring associations has received extensive documentation in the fields of paleoecology and ichnology. The basis for this recurrence stems from the concept that ichnofossils are the preserved record of behaviour and functional morphology and therefore, reflect adaptations of organisms to particular ecological conditions (Frey and Pemberton, 1985). Ichnofossil associations characteristic of particular environmental regimes are recurrent in space and time whenever the requisite environmental conditions occur (Frey and Seilacher, 1980; Frey and Pemberton, 1985).

3.2.1 *Skolithos -Planolites* Association

Ichnofossil association 1 is represented by very low diversity assemblages of isolated small *Planolites* and *Skolithos* (Fig. 3.1). One of the characteristic features of this association is the diminutive size of the ichnofossils. *Skolithos* shafts are less than 2 cm in length and 1-2 mm in diameter, while *Planolites* burrows range form 0.5 to 2 mm in diameter. Ethologically, these biogenic structures (vertical shafts and horizontal burrows) can be considered to reflect simple, nonspecialized behaviour. This association has been observed in all facies, but is particularly common in the interbedded sandstones and mudstones (Facies 7) and the small-scale cross-stratified sandstones (Facies 3). This suggests that the occurrence of this ichnofossil association is not lithologically-controlled or substrate dependent. Rather, other environmental factors (*eg*. salinity, oxygenation, nutrient availability *etc*.) appear to have been limiting factors in the distribution of ichnofossils. The diminutive size, morphologic simplicity of the structures and the low diversity of the ichnofossil which comprise this association are interpreted to reflect harsh physiological conditions associated with a brackish water environment .

ICHNOFOSSILS	ICHNOFOSSIL ASSOCIATIONS							
	1	2	3	4	5	6	7	8
Asterosoma	-	-	-	r	-	c	c-o	-
Bergaueria	-	-	-	-	-	-	r	-
Chondrites	-	-	-	r	-	-	-	a
Conichnus	-	-	-	-	-	-	o-r	-
Cylindrichnus	-	o	o - r	-	-	-	c-o	-
Gyrolithes	-	c	a	-	-	-	-	-
Helminthopsis	-	-	-	-	-	-	r	c-o
Macaronichnus	-	-	-	-	-	-	c-o	-
Palaeophycus	-	-	-	-	-	c	a	-
Planolites	o-r	a	c-o	c-o	o-r	c	a	o-r
Rhizocorallium	-	-	-	r	-	-	r	-
Rosselia	-	o-r	o-r	-	-	-	a-c	-
Skolithos	o-r	a	c-o	c-o	-	r	a	-
Teichichnus	-	-	-	a	-	c-o	c-o	-
Terebellina	-	-	-	-	-	-	o-r	-
Zoophycos	-	-	-	-	-	-	-	c

Table 3.2 Relative abundance and distribution of ichnofossils occurring within the recurring ichnofossil associations observed within the Grand RapidsFormation.

a=abundant, c=common, o=occassional, r=rare, - =not present

Figure 3.1 ***Skolithos-Planolites*** **association**

a) and b) Fine-grained small-scale cross-stratified sandstones with thin mudstone partings. Note the bioturbated bed tops and partings which are characterized by ichnofossil assemblages dominated by small *Skolithos* and *Planolites*. The photographs are from 6-6-62-1W4, 327-330 m (GR_4 lithosome). Scale bar gradations are in centimeters.

c) and d) Interbedded sandstones and mudstones which are characterized by non-descript burrows, primarily *Planolites* and shafts (*Skolithos*). Photograph 3.1 c is from 13-2-61-2W4, 388.3 m (GR_2 lithosome). Scale bar gradations are in centimeters.

A
B
C
D

3.2.2 *Skolithos* Association

This ichnofaunal association typifies fine-grained, cross-stratified (Facies 3 and 4) and planar-laminated (Facies 5) sandstones and is represented by moderate density and low diversity ichnofossil assemblages which may include the following ichnofossils: *Skolithos*, *Planolites*, *Gyrolithes* and minor to rare *Cylindrichnus*, *Rosselia* and *Monocraterion* (Fig. 3.2). This association consists predominantly of vertical dwelling and feeding structures created by suspension-feeding organisms, however deposit-feeding structures (*Planolites* and *Rosselia*) are common locally. The predominance of biogenic structures created by suspension-feeding organisms is suggestive of agitated, nutrient-rich and well-oxygenated bottom waters. Currents were of sufficient magnitude to suspend nutrients within the water column, but were moderate enough to allow organic detritus to settle from suspension, offering nutrient resources to deposit-feeding organisms and shallow suspension-feeding organisms. The characteristics of this association; the predominance of vertical dwelling structures, the generally low diversity and moderate burrow density, is for the most part, indicative of the *Skolithos* ichnofacies.

Bedding units characterized by this ichnofossil association typically consist of alternating bioturbated and laminated or cross-stratified beds. The bioturbated beds consist of low diversity, *Skolithos*-dominated assemblages, whereas escape structures are the only biogenic structures observed in the laminated beds. This alternation of laminated and bioturbated bedding units is interpreted to reflect the dynamic interplay between higher energy events and background, fairweather sedimentation. Laminated zones reflect energetic periods in which benthic boundary layer shear stress could not be tolerated by the benthic community. Bioturbated beds record periods in which current velocities were sufficiently reduced, permitting organisms to rework the substrate.

3.2.3 *Gyrolithes* Association

Association 3 is characterized by very low diversity to monospecific ichnofaunal assemblages which are dominated by *Gyrolithes* (Fig. 3.3). Associated ichnofossils include

Figure 3.2 *Skolithos* association

a) Fine-grained, muddy planar-laminated sandstone characterized by low diversity to monospecific ichnofossil assemblages dominated by *Skolithos*. Typically ichnofossil diversity is very low, although, burrow density may be high. The photograph is from 5-10-60-2W4, 370 m (GR_4 lithosome). Scale bar gradations are in centimeters.

b) Fine-grained, micaceous massive sandstone characterized by low diversity ichnofossil assemblages dominated by a large form of *Skolithos* , up to 30 cm in length and 5 mm in width. The photograph is from 13-2-61-2W4, 375.5 m (GR_3 lithosome). Scale bar gradations are in centimeters.

c) Medium-grained massive sandstone characterized by low diversity ichnofossil assemblages dominated by a small form of *Skolithos*. The photograph is from 13-2-61-2W4, 373 m (GR_3 lithosome). Scale bar gradations are in centimeters.

A
B
C

Figure 3.3 *Gyrolithes* association

a) and b) Fine-grained planar-laminated sandstone characterized by monospecific ichnofossil assemblages of *Gyrolithes*. One of the characteristic features of this ichnofossil is its restriction to distinct narrow intervals parallel to bedding. The photographs are from 7-1-62-2W4, 319-321 m (GR_3 lithosome). Scale bar gradations are in centimeters.

C

minor to rare *Cylindrichnus*, *Planolites*, *Skolithos* and *Rosselia*. This ichnofossil association is for the most part restricted to the planar-laminated sandstones (Facies 5) which are abundant in the upper portions of the Grand Rapids Formation. The intensity of bioturbation is generally low, but the unique feature of this association is the occurrence of horizons which are pervasively bioturbated almost exclusively with *Gyrolithes*. The low diversity to monotypic nature of this association may reflect extremely stressful environmental conditions such as brackish water conditions.

The morphology of *Gyrolithes* is interpreted to reflect a burrowing adaptation to escape extreme salinity fluctuations at the sediment-water interface (Gernant, 1972; Powell, 1977). The *Gyrolithes* -making organism had the ability to rapidly retract within the sediment removed from extreme physical and chemical stresses at the sediment-water interface. Gernant (1972) suggested that the *Gyrolithes* trace-making organism was restricted to marginal marine strata and therefore *Gyrolithes* may be utilized as a brackish water indicator. Although paleoenvironmental interpretations constructed on the basis of one sedimentary structure should be avoided; it is interesting to note that other lines of sedimentologic evidence are indicative of a brackish water depositional environment, suggesting this assumption may have some validity in this particular case.

3.2.4 *Teichichnus* Association

Interlaminated mudstones (Subfacies 1b) are typified by low diversity ichnofossil assemblages dominated by *Teichichnus* (Fig. 3.4); associated ichnofossils include *Planolites* and *Skolithos* and rare *Asterosoma*, *Chondrites*, *Gyrolithes* and *Rhizocorallium*. This association is characterized by a predominance of horizontal deposit-feeding structures (*Teichichnus*, *Planolites*, *Asterosoma*, *Chondrites*) with common, but subordinate occurrences of dwelling structures (*Skolithos* and *Gyrolithes*). Although diversity is low, individuals, particularly *Teichichnus*, may attain very high densities. Areas of high density *Teichichnus* are commonly represented by a wispy, bioturbate texture in which distinct, recognizable spriete and other burrow elements are not always readily apparent. Such ichnofaunal assemblages are characteristic of a mixed *Skolithos*-

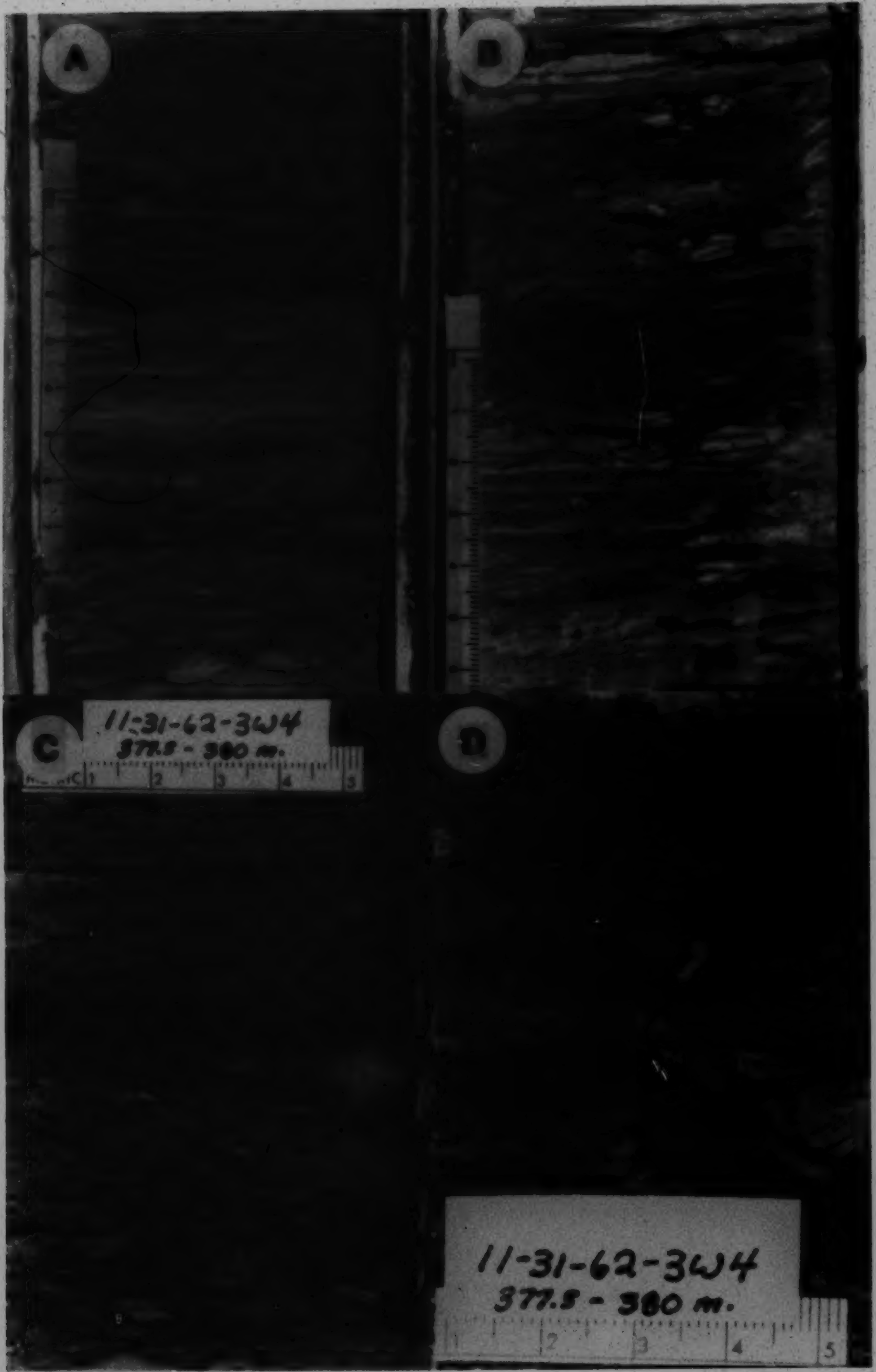
Figure 3.4 *Teichichnus* association

a) Interlaminated mudstone with low diversity, high density ichnofossil assemblages dominated by *Teichichnus*. Note the alternation of thoroughly bioturbated and non-bioturbated zones. Photograph is from 7-1-62-2W4, 379.5 m (GR_3 lithosome). Scale bar gradations are in centimeters.

b) Interlaminated mudstone and siltstone with *Teichichnus* -dominated ichnofossil assemblages. *Planolites*, *Palaeophycus*, *Skolithos* and *Cylindrichnus* are also present within the field of the photograph. The photograph is from 5-10-60-2W4, 407 m (GR_2 lithosome). Scale bar gradations are in centimeters.

c) Thoroughly bioturbated interlaminated mudstone. The photograph is from 11-31-62-3W4, 377.5-378m (GR_2 lithosome). Scale bar gradations are in centimeters.

d) Close up view of 3.4 c. Note the distinct, well-formed retrusive spriete within the *Teichichnus* burrows and the isolated *Planolites* and *Skolithos*. The photograph is from 11-31-62-3W4,377.5- 378m(GR_2 lithosome). Scale bar gradations are in centimeters.


A
B
C
D
11-31-62-3W4
377.5 - 380 m.
11-31-62-3W4
377.5 - 380 m.

Cruziana ichnofacies which has been interpreted by many authors as being diagnostic of brackish water environments (Howard and Frey, 1973, 1975, 1985; Dörjes, 1977; Ekdale *et al.*, 1984, Frey and Pemberton, 1985; Wightman *et al.*, 1987).

One of most significant features of this association is the consistent stratigraphic position it occupies, immediately overlying transgressive flooding surfaces. Typically beds displaying the *Teichichnus* association are found abruptly overlying thin coals or rooted, carbonaceous mudstones which are devoid of biogenic structures. Thus the occurrence of this ichnofossil association records the re-establishment of the benthic community in response to more favourable physical and ecological conditions following a relative sea level rise.

The ichnological signature of this association has considerable implications, the low diversity, often monotypic nature of the ichnofossil assemblages is suggestive of a salinity stressed or brackish water environment. The presence of this ichnofossil association immediately overlying the transgressive flooding surfaces within the Grand Rapids Formation suggests that the transgressive events did not inundate the area with fully saline marine waters. Instead, the salinity of the depositional basin, possibly due to depth, circulation, basin configuration, fluvial input or magnitude of the sea level rise apparently did not achieve open marine conditions.

3.2.5 *Planolites* association

This association is predominantly restricted to carbonaceous (Subfacies 1d) and laminated mudstones (Subfaices 1c), but locally is found within interlaminated mudstones (Subfacies 1b). The relative degree of bioturbation is characteristically extremely low and represented by low density, monospecific assemblages of *Planolites* (Fig. 3.5). Accessory features include syneresis cracks, abundant carbonaceous debris, both as laminae and as disseminated matter, and siderite concretions.

The nature of this association, argillaceous sediments and horizontal, deposit-

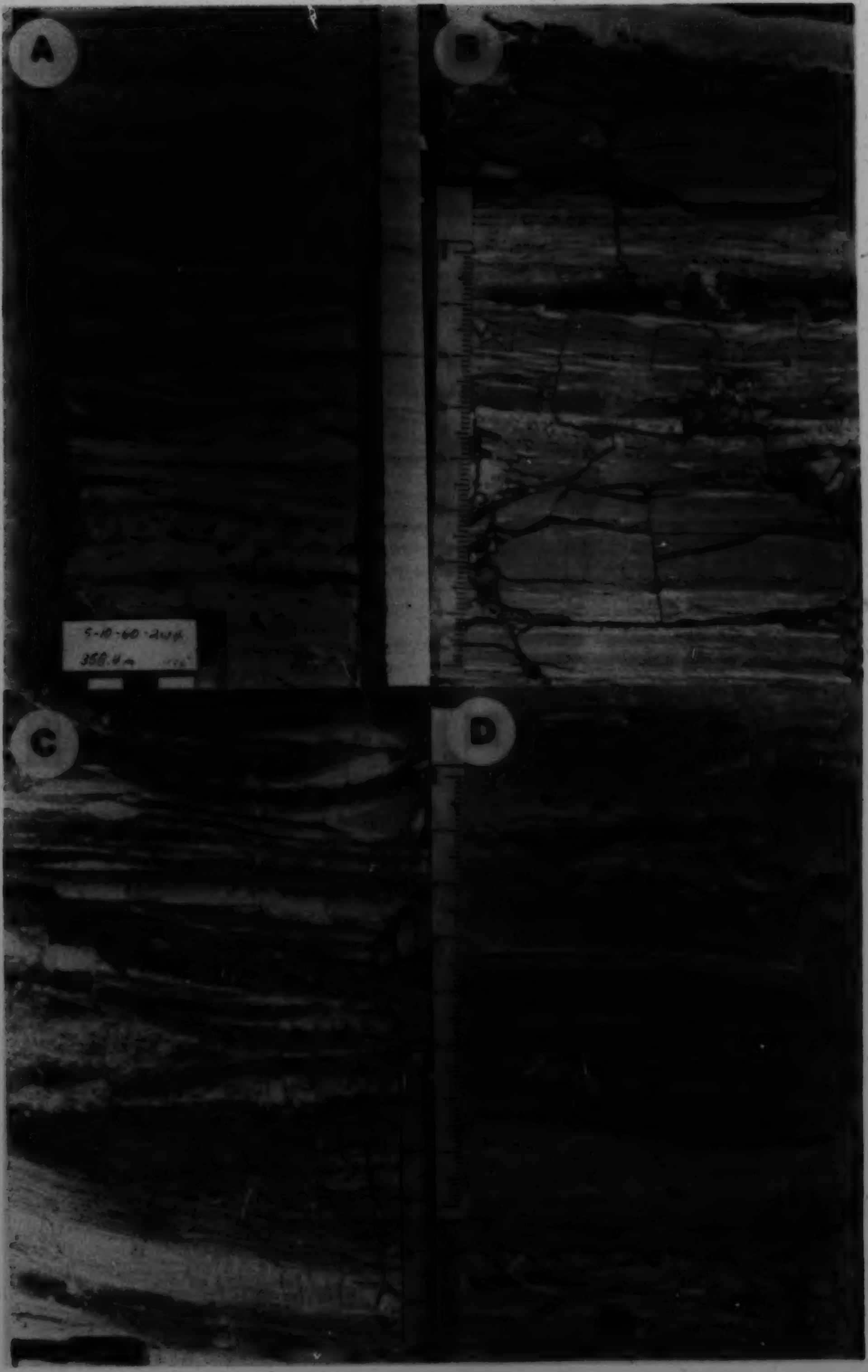
Figure 3.5 *Planolites* association

a) Interbedded small-scale cross-stratified sandstones and carbonaceous mudstones (subfacies 7b) exhibiting monospecific ichnofossil assemblages consisting of a small form of *Planolites*. Note the abundance of syneresis cracks in the mudstones. The photograph is from 5-10-60-2W4, 358.4 m (GR_5 lithosome). Scale bar gradations are in centimeters.

b) Thinly laminated mudstone (subfacies 1c) with isolated *Planolites*. The photograph is from 13-2-61-2W4, 338 m (GR_5 lithosome). Scale bar gradations are in centimeters.

c) Thinly laminated mudstone (subfacies 1c) with silty mudstone partings which exhibit low density, monospecific ichnofossil assemblages of *Planolites*. The photograph is from 7-1-62-2W4, 335 m (GR_5 lithosome). Scale bar gradations are in centimeters.

d) Thinly laminated mudstone (subfacies 1c) with isolated *Planolites* and synersis cracks. The photograph is from 13-2-61-2W4, 393 m (GR_3 lithosome). Scale bar gradations are in centimeters.


A
B
C
D
5-10-60-20W4
356.4m

feeding structures, is suggestive of the *Cruziana* ichnofacies. However, it is the monospecific nature and low density of biogenic structures which have the most significant implications concerning the nature of the depositional environment. The monospecific nature of this association is interpreted to reflect reducing or anoxic conditions which developed in a restricted setting. The low relative intensity of bioturbation suggests that bottom waters were not sufficiently oxygenated to support a diverse, oxygen-dependent benthic community. Oxygenation of the water column is important to all benthic organisms, however some taxa have the capability to tolerate and may even preferentially inhabit low oxygen or oxygen-depleted ecological niches (Ekdale, 1988). The inferred nature of the *Planolites* trace-making organism (*i.e.* endostratal deposit-feeding) suggests that although sediments may have been organic-rich, the interstitial environment was not completely devoid of oxygen. Thinly laminated zones devoid of biogenic structures imply that periodically, anoxic conditions may have been established. Prolonged periods during which the interstitial environment and/or the overlying water column were oxygen-depleted would be lethal to benthic organisms (Rhoads and Moorse, 1971; Ekdale, 1985).

The distinct absence of biogenic structures created by suspension-feeding organisms implies that the physical and ecological conditions of the depositional environment could not sustain a suspension-feeding community. In low oxygen environments, sediments commonly contain high concentrations of unoxidized organic matter which may support dense deposit-feeding communities. Such environments are typically stagnant and devoid of currents of sufficient strength to suspend nutrients in the water column. As a result, low oxygen environments are typified by a predominance of deposit-feeding organisms and a general absence of suspension-feeding organisms. Thereore, the ichnological signature of oxygen-depleted deposits consists of high density, low diversity ichnofossil assemblages dominated by deposit-feeding structures.

Alternatively other environmental factors such as variable and low salinities may also have imposed severe physiological stresses on benthic organisms and resulted in the preferential exclusion of suspension-feeding organisms. Burrowing, especially deep burrowing, is an adaptation which provides benthic organisms the capability of withstanding salinity fluctuations due to the buffering capacity of sediments (Wightman *et al.*., 1987). Sanders *et al.* (1965) investigated salinity fluctuations in the water and sediments of the Pocasset River Estuary. They found that while salinity values at the sediment-water interface and overlying water column fluctuated from 2.3 ppm. to 29.3 ppm. during a single tidal cycle, salinity values from the interstitial environment (depth = 5-20 cm.) remained relatively constant at 20.5 ppm. Therefore, even shallow burrowing organisms are significantly removed from the harsh physical and chemical environment of the sediment-water interface and overlying water column. Thus, because of the ability of deposit-feeding organisms to flourish within the interstitial environment they may have been able to escape or tolerate harsh ecological conditions that suspension-feeding organisms and other epibenthic organism could not withstand. Deposit-feeding organisms may have preferentially inhabited a stressful ecological niche because of low levels of interspecific competition (Ekdale *et al*, 1985).

The abundance of siderite concretions compliments the interpretation of anoxic or reducing conditions. The formation of siderite is enhanced when interstitial pore waters are depleted with respect to free oxygen and dissolved sulfur. Thus the presence of siderite may be suggestive of rapid accumulation and decomposition of organic matter in a restricted, anoxic or oxygen-limited environment (Gauthier, 1982). It is not clear if the overlying water column was oxygen-depleted, however the low diversity and density of biogenic structures, abundance of siderite and the carbonaceous nature of the sediments suggests that the interstitial waters were not well oxygenated. Syneresis cracks are a very common accessory sedimentary structure found with argillaceous beds which display this ichnofossil association. Syneresis cracks develop in response to extreme salinity fluctuations (Burst, 1965; Plummer and Gostin, 1981) and , in absence of structures indicative of loading or dewatering, they may provide evidence that the depositional environment was subject to periodic, extreme salinity fluctuations (Wightman et al., 1987).

The monospecific nature of this ichnofossil association combined with the highly carbonaceous nature of the mudstones, is interpreted to reflect harsh ecological conditions, particularly low, but variable salinity and/or anoxic or oxygen-restricted conditions. This suggests that both salinity and oxygenation may have been limiting factors in the distribution of benthic organisms. It is difficult to discern whether these factors independently or dependently influenced the distribution of benthic organisms. Regardless of which was the dominant factor, the low density, monospecific assemblages indicates that only a limited number of benthic organisms could flourish in this unstable or unpredictable setting. Organisms which inhabit unstable environments, such as estuaries and other marginal marine environments, typically have broad environmental tolerances and can adapt to environmental disturbances. Such organisms, because they are subjected to high levels of physiological stress, tend to exhibit opportunistic or r-selected population dynamics (Ekdale, 1985). In contrast, benthic organisms which inhabit stable or predictable environments are more severely affected by physical or biological stresses such as variable salinity or oxygenation levels. Conditions of abundant organic matter, fluctuating salinity and low concentrations of dissolved oxygen are common in estuarine and delta plain environments in which large volumes of organic-rich mud are deposited in restricted settings.

3.2.6 *Palaeophycus -Planolites* association

This ichnofossil association typifies laminated to bioturbated mudstones (Subfacies 1c) and is represented by low diversity and low density assemblages consisting of *Planolites*, *Palaeophycus*, *Asterosoma*, *Skolithos* and common *Teichichnus*, with rare *Gyrolithes* (Fig. 3.6). In addition, numerous beds are characterized by a bioturbate texture, in which very few discrete ichnofossils can be identified. The homogeneous nature of these argillaceous sediments reflects intense sediment reworking by abundant foraging and burrowing organisms. This association is suggestive of a benthic community dominated by deposit-feeding and carnivorous organisms and is mainly indicative of the *Cruziana* ichnofacies. The dwelling structures (*Gyrolithes* and *Skolithos*) are restricted to thin, sharp-based beds of laminated and cross-stratified sandstones, indicative of a shifting, particulate substrate and suggestive of the *Skolithos* ichnofacies. The occurrence of these beds reflect deposition above wave base, definitely storm wave base and possibly

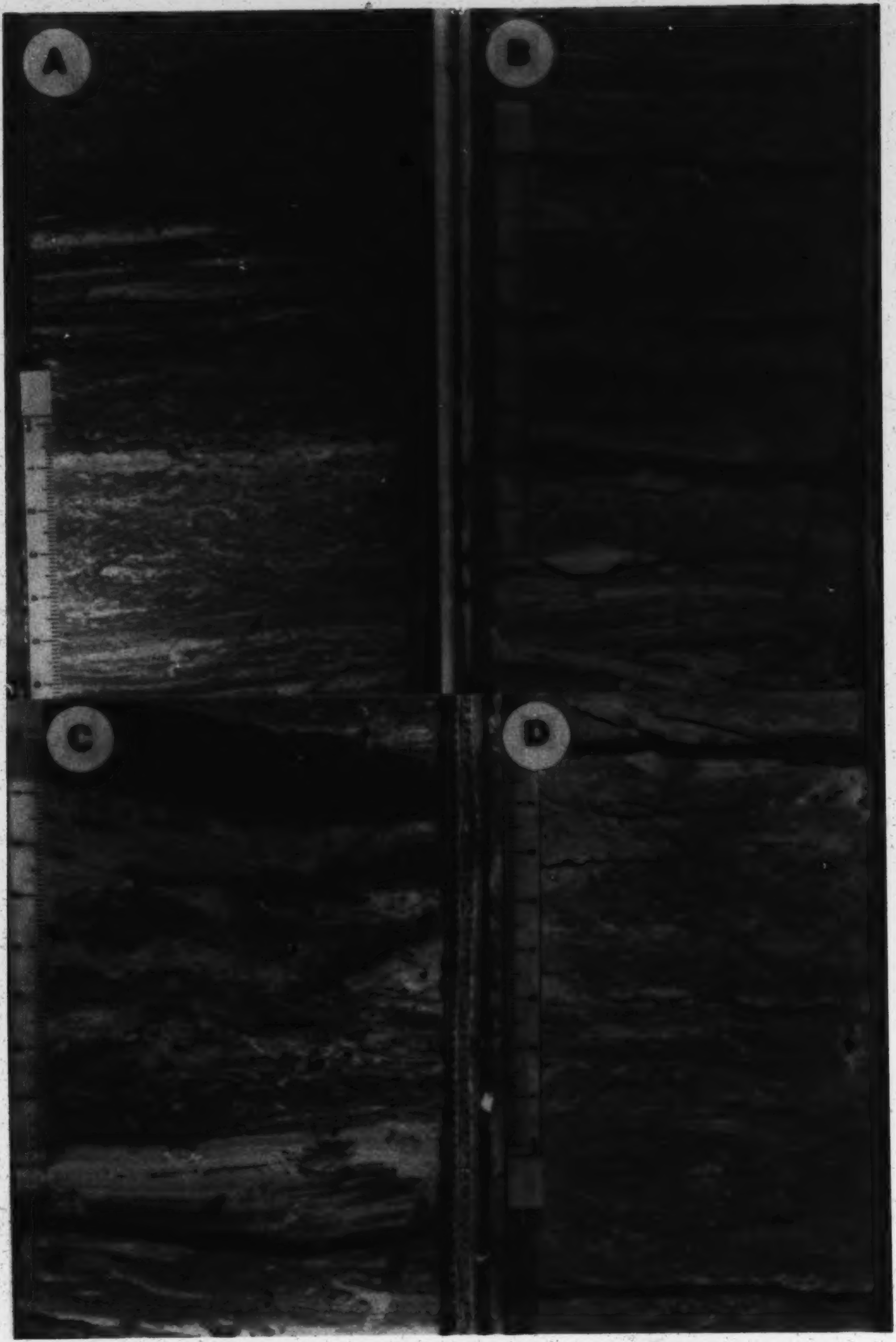
Figure 3.6 *Palaeophycus-Planolites* association

a) Interlaminated mudstone which are characterized by low diveristy, high density ichnofossil assemblages dominated by *Palaeophycus*, *Planolites* and *Skolithos*. Associated ichnofossils include *Teichichnus*, *Cylindrichnus* and *Asterosoma*. Note the alternation of bioturbated and non-bioturbated. The photograph is from 7-1-62-2W4, 378 m, (GR_2 lithosome). Scale bar gradations are in centimeters.

b) Laminated mudstone (subfacies 1c) with low density, low diversity ichnofossil assemblages dominated by *Palaeophycus* and *Skolithos*. The photograph is from 16-9-62-1W4, 362.5 m (GR_4 lithosome). Scale bar gradations are in centimeters.

c) Very fine-grained small-scale cross-stratified sandstone with low diversity ichnofossil assemblages dominated by *Palaeophycus*. The photograph is from 5-10-60-2W4, 362.3 m (GR_5 lithosome). Scale bar gradations are in centimeters.

d) Interlaminated mudstones which are characterized by low diveristy, high density ichnofossil assemblages dominated by *Palaeophycus*. The photograph is from 5-10-60-2W4, 366.3 m (GR_5 lithosome). Scale bar gradations are in centimeters.


A
B
C
D

fairweather wave base. Emplacement of these beds do not represent sudden shallowing events, but rather a temporary lowering of wave base in response to coastal upwelling associated with meteorological disturbances. The occurrence of these dwelling structures may represent the displacement of the resident benthic community by high physiological stresses associated with the deposition of the sandstone beds (storm or flood event). Following this event opportunistic species, represented here by *Gyrolithes* and *Skolithos*, invaded the recently deposited sediments. With the return to normal, fairweather conditions the resident deposit-feeding community was re-established and the opportunistic, suspension-feeding community was eventually displaced. Similar event-related, examples of ichnological dynamics have been documented from ancient shallow marine deposits (*cf.* Frey and Seilacher, 1980; Pemberton and Frey, 1984; Vossler and Pemberton, 1988).

The overall increase in ichnotaxonomic diversity of this ichnofossil association relative to that of the *Planolites* association reflects a fundamental change in organism behaviour. This change may have been a function of variations in a number of environmental parameters such as nutrient supply, sediment consistency, degree of oxygenation and/or salinity. The effect was the establishment of physical and biological conditions that were more conducive to benthic colonization.

3.2.7 *Skolithos-Palaeophycus* association

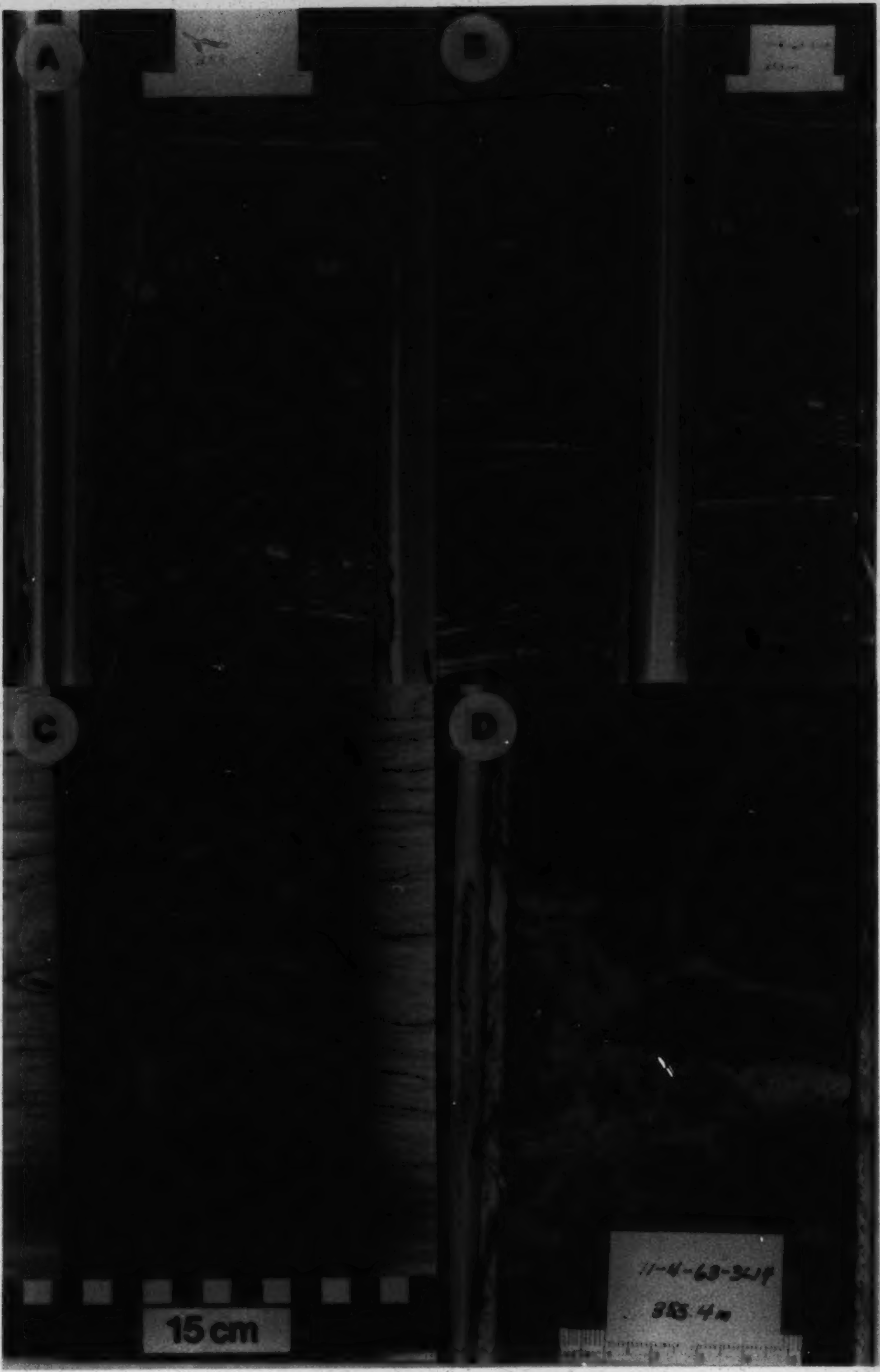
Ichnofossil association 7 typifies the bioturbated sandstones (Facies 2) of the lowermost portions of the Grand Rapids Formation. It is characterized by high diversity and moderate density ichnofossil assemblages which may include the following ichnofossils: ***Asterosoma*, *Bergaueria Conichnus*, *Cylindrichnus*, *Macaronichnus*, *Planolites*, *Palaeophycus*, *Rhizocorallium*, *Skolithos*, *Teichichnus*** and ***Terebellina*** (Fig. 2.7). Locally beds may be thoroughly bioturbated and discrete ichnofossils cannot be recognized; instead, these beds are characterized by a pervasive bioturbate texture. This association is represented by a mixture of dwelling, feeding and combination dwelling-feeding structures created by both deposit- and suspension-feeding organisms and is considered to be representative of a mixed *Skolithos* - *Cruziana* ichnofacies.

Figure 3.7 ***Skolithos-Palaeophycus*** **association**

a) and b) Large-scale cross-stratified sandstone characterized by low density, low divesity ichnofossil assemblages dominated by *Skolithos* and *Paleophycus*. Note the thick wall linings of the*Skolithos* burrows. The photographs are from 11-4-63-3W4, 353-355m (GR_2 lithosome). Scale bar gradations are in centimeters.

c) Fine-grained, bioturbated sandstone which display high diversity, high density ichnofossil assemblages containing small and large forms of *Planoites, Palaeophycus, Skolithos* and *Asterosoma*. The photograph is from 12-31-61-1W4, 391 m (GR_1 lithosome). Scale bar gradations are in centimeters.

d) Thoroughly bioturbated sandstone with possible large *Cylindrichnus*. Many examples of the *Skolithos-Palaeophycus* association are characterized by a similar non-descript, bioturbate texture. The photograph is from 11-4-63-3W4, 355.4 m (GR_1 lithosome). Scale bar gradations are in centimeters.


A
B
C
D
15 cm
11-4-63-3W4
353.4m

The most diagnostic feature of this association is the marked increase in ichnotaxonomic diversity relative to all other ichnofossil assemblages. This is interpreted to reflect optimal ecological conditions associated with a stable, predictable environmental setting. Sedimentation is presumed to be relatively continuous and slow because of the preservational bias of biogenic structures relative to physical structures. The consistently high relative intensity of bioturbation implies periods of prolonged fairweather conditions with only minor evidence of physical reworking in response to storms or other energetic physical processes. Environmental conditions such as salinity, nutrient availability, oxygenation and substrate consistency, as reflected in the diversity of the association, are interpreted to have been optimal for the development of a stable benthic community of both suspension- and deposit-feeding organisms. Within a typical beach to offshore profile such optimal ecological and sedimentological conditions would be found within the lower shoreface environment (*cf.* Howard, 1975; Dörjes and Howard, 1975; Howard and Frey, 1984, Frey and Howard, 1985).

3.2.8 *Zoophycos* Association

This ichnofossil association, as with the *Skolithos-Palaeophycus* association, characterizes the argillaceous (Subfacies 1c) and heterolithic facies (Subfacies 7a and 7b) of the GR_1 lithosome, and is represented by the occurrence of *Zoophycos, Helminthopsis* and *Chondrites*. The nature of this association sharply contrasts with those that characterize the bulk of the Grand Rapids Formation, in that it is dominated by complex deposit-feeding structures (*Zoophycos* and *Chondrites*) and fecal castings (*Helminthopsis*). Such an assemblage is interpreted to be indicative of normal marine shelfal conditions of the *Cruziana* or proximal *Zoophycos* ichnofacies.

These ichnofossils reflect highly specific feeding strategies employed by a benthic community to cope with particular ecological conditions. K-selected or equilibrium species tend to inhabit stable, biologically-controlled environments. The limited nutrient supply combined with high levels of intraspecific competition, imposed upon the benthic organisms the need to adapt optimal feeding strategies. The complex systematic nature of organisms the need to adapt optimal feeding strategies. The complex systematic nature of the ichnofossils of this association contrast with the simple nature of the predominantly r-selected ichnotaxa which characterizes the majority of the assemblages observed within the Grand Rapids Formation.

3.3 Synthesis of paleoenvironmental implications

Although the recurring ichnofaunal assemblages have significant paleoenvironmental implications, the overall ichnofossil suite is characterized by:

(1) generally low to very low diversity;
(2) an impoverished marine assemblage;
(3) reduced size compared to fully-marine counterparts;
(4) dominance of morphologically simple, vertical and horizontal structures; and
(5) a mixture of elements which are common to both the *Skolithos* and *Cruziana* ichnofacies.

The overall low ichnotaxonomic diversity which characterizes the majority of the recurring ichnofaunal associations delineated from the Grand Rapids Formation parallels diversity trends documented from modern brackish water environments. Faunal assemblages in modern brackish water environments are typically reduced with respect to species diversity compared to freshwater and fully-marine counterparts. This low diversity is a reflection of the limited number of benthic species which have evolved the physiological specialization necessary to inhabit brackish water environments (Barnes, 1984). Very few freshwater species are capable of withstanding salinities greater than 35 ppm; similarly very few marine species can tolerate salinities less than 18 ppm.

The freshwater and fully marine faunas represent stable end-members at opposing ends of a salinity gradient. With even a slight increase in salinity, the diversity of the freshwater faunal component declines rapidly. In contrast, with decreasing salinity the diversity of the fully marine component declines at a more gradual rate. Therefore, the brackish water faunal assemblage more appropriately represents an impoverished marine assemblage rather than a true mixture of freshwater and marine components (Ekdale *et al.*, 1984; Wightman *et al.*, 1987). Such diversity trends observed in the distribution of modern benthic organisms are reflected to some extent in the ancient sedimentary record by the occurrence of low diversity to monospecific ichnofossil assemblages. Various authors have suggested that such characteristically low levels of ichnotaxonomic diversity reflect harsh ecological parameters and may potentially be utilized as a paleo-indicator of brackish water conditions (*cf.* Frey and Howard, 1975, 1980, 1985; Ekdale *et al.*, 1984; Wightman *et al.*, 1987).

In addition to a decrease in species diversity, benthic organisms which inhabit brackish water environments typically display a reduction in size relative to their fully-marine counterparts. This trend is not apparent in freshwater species (Barnes, 1984) which have the ability to adapt to low saline conditions (Remain and Schlieper, 1971). The relative reduction in size is an adaptive, morphological response evolved by predominantly marine organisms to tolerate the high, salinity-induced physical and chemical stresses which inhabiting brackish water environments imposes. Lowered salinity affects the size of benthic organisms in a number of ways, including: decreased metabolism, retarded growth and development, promotion of an early onset of sexual maturity, among others (Remain and Schlieper, 1971). Furthermore, the rigours of inhabiting brackish waters imposes an increased demand for oxygen on benthic organisms. By decreasing their effective surface area these organisms can decrease their total oxygen consumption and therefore function more efficiently. This reduction in size also serves as an adaptation to facilitate osmo-regulation of internal body chemistry due to salinity fluctuations (Remain and Schlieper, 1971).

The relative morphologic simplicity of the ichnofossils reflects the non-specialized feeding strategies employed by the trace-making community. Such organisms are opportunistic in nature and display r-selected strategies in population dynamics. Opportunistic organisms flourish in environments of high physiological stress, such as brackish water settings, where animal communities are not resource-limited

(Levington,1970; Grassle and Grassle, 1974). Opportunistic or r-selected organisms are characterized by rapid reproduction and growth rates, small body size, short life cycles, broad environmental tolerances and nonspecialized feeding strategies (Levington, 1970; Jones, 1981; Ekdale, 1985). Such organisms are particularly well suited to high stress and/or low resource environments (Ekdale, 1985). In contrast, K-selected or equilibrium species are characterized by lower reproduction and growth rates, larger body size, narrow environmental tolerances and highly specialized feeding strategies (Levington, 1970; Jones, 1981; Ekdale, 1985). Such organisms typically predominate in stable, biologically controlled environments (Levington, 1970). The specialized feeding strategies employed by such organisms are a consequence of high levels of interspecific competition and resource limitation. Such environmental conditions imposes upon organisms the necessity to evolve the most energy efficient means of acquiring nutrients, typically this resulting in the occupation of very specialized ecological niches. Ichnofossils representing complex feeding strategies (*ie. Zoophycos*, *Rhizocorallium*, *Paleodictyon etc.*) are, for the most part, absent from the Grand Rapids Formation.

The overall character of the ichnology of the Grand Rapids Formation is perhaps best represented by a mixed *Skolithos-Cruziana* ichnofacies. This ichnofacies typically consists of a mixture of vertical and horizontal structures common to both the *Skolithos* and *Cruziana* ichnofacies. As previously mentioned, the presence of such an assemblage has been interpreted by many authors as being somewhat diagnostic of brackish water conditions (Howard and Frey, 1975, 1985; Dorjes, 1977; Ekdale et al., 1984, Frey and Pemberton, 1985; Wightman et al., 1987). The environmental significance of this ichnofacies is becoming increasing apparent as the number of ichnological studies focusing specifically on marginal marine environments increases. Howard and Frey (1975) and Frey and Pemberton (1985) suggested that this ichnofacies is indicative of a specific array of ecological parameters, which appear to be independent of bathymetry, geomorphology or geographic setting. Instead they appear to be related to physical and chemical parameters, in particular, reduced and variable salinities, associated with marginal marine, brackish water environments.

3.4 Conclusions

The Lower Cretaceous Grand Rapids Formation within the Cold Lake oil sands area is characterized by several well-developed brackish water ichnofossil associations. Fifteen ichnogenera have been recognized: *Asterosoma, Bergaueria, Chondrites, Cylindrichnus, Gyrolithes, Helminthopsis, Macaronichnus, Monocraterion, Palaeophycus, Planolites, Rhizocorallium, Rosselia, Skolithos* , *Teichichnus* and *Zoophycos* . In addition, nondescript, passively-filled burrows and fugichnia (escape structures) were observed. These ichnogenera appear to occur systematically within the Grand Rapids Formation as eight distinct, recurring ichnofossil associations.

The majority of the recurring ichnofossil associations observed within the Grand Rapids Formation are characterized by a mixture of simple, horizontal and vertical structures common to both the *Skolithos* and *Cruziana* ichnofacies. The simple nature of these ichnofossils is a reflection of the nonspecialized feeding strategies employed by the trace-making organisms. Such animals are opportunistic in nature and display an r-strategy in population dynamics. Typically the individual ichnofossils of this assemblage are reduced in size compared to their respective fully marine analogues. This relative size reduction is an adaptive response to the high, salinity-related, physical and chemical stresses imposed on the osmo-regulatory apparatus of the trace-making community. Furthermore, although bioturbation may be intense in argillaceous sediments, ichnotaxonomic diversity is characteristically very low. These aforementioned characteristics suggest that salinity was a dominant limiting factor on bioturbation and ichnofossil distribution. The *Skolithos -Palaeophycus* and *Zoophycos* ichnofossil associations, which are restricted to the uppermost portion of the Clearwater Formation and the lowermost portion of the Grand Rapids Formation, are exceptions to the preceding general statements. These two ichnofossil associations are characterized by high diversity, high density ichnofossil assemblages that display k-selected or equilibrium feeding strategies suggestive of a stable, non-stressed, normal marine shelf setting. The distribution of these two ichnofossil associations suggests that at the close of Clearwater Formation deposition and the onset of Grand Rapids Formation deposition normal marine conditions prevailed. However, the majority of the Grand Rapids Formation appears to have been characterized by brackish water conditions.

The presence of several well-developed brackish water ichnofossil associations has important local and regional paleoenvironmental implications. On a local scale, this implies that although salinity levels fluctuated, brackish water conditions prevailed throughout much of the deposition of the Grand Rapids Formation. On a regional scale this may imply that fully marine conditions may not have been attained during deposition of the Mannville Group within this portion of the Alberta Basin and that brackish water conditions were more extensive in the Mannville Group than presently interpreted.

CHAPTER 4 FACIES ASSOCIATIONS AND DEPOSITIONAL HISTORY

4.1 Introduction - Recurring Facies Associations

The seven facies described in Chapter 2 can be arranged into four distinct, recurring facies associations. The term "facies association", in the context of this discussion, refers to distinct successions of facies which are considered to be environmentally or genetically related (*cf.* Reading, 1986). The strength of grouping individual facies into facies associations is that each facies can be placed in context with other facies that are interpreted to be genetically related. In such a framework each facies contributes to the interpretation of other facies (Walker, 1990).

4.1.1 Facies Association 1 (marine shelf-shoreface deposits)

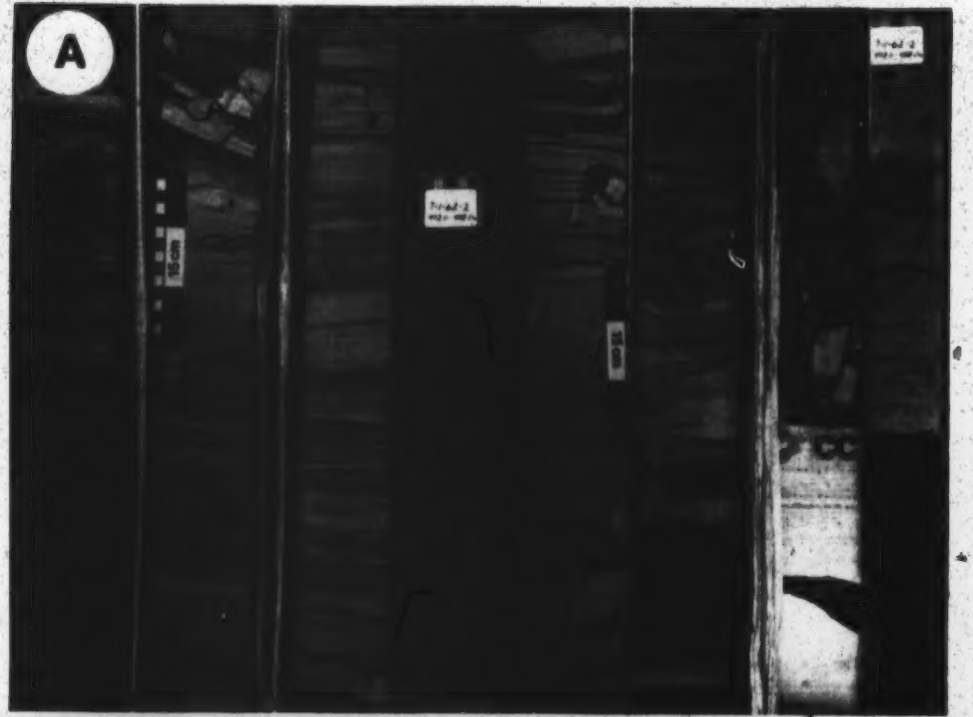
Description:

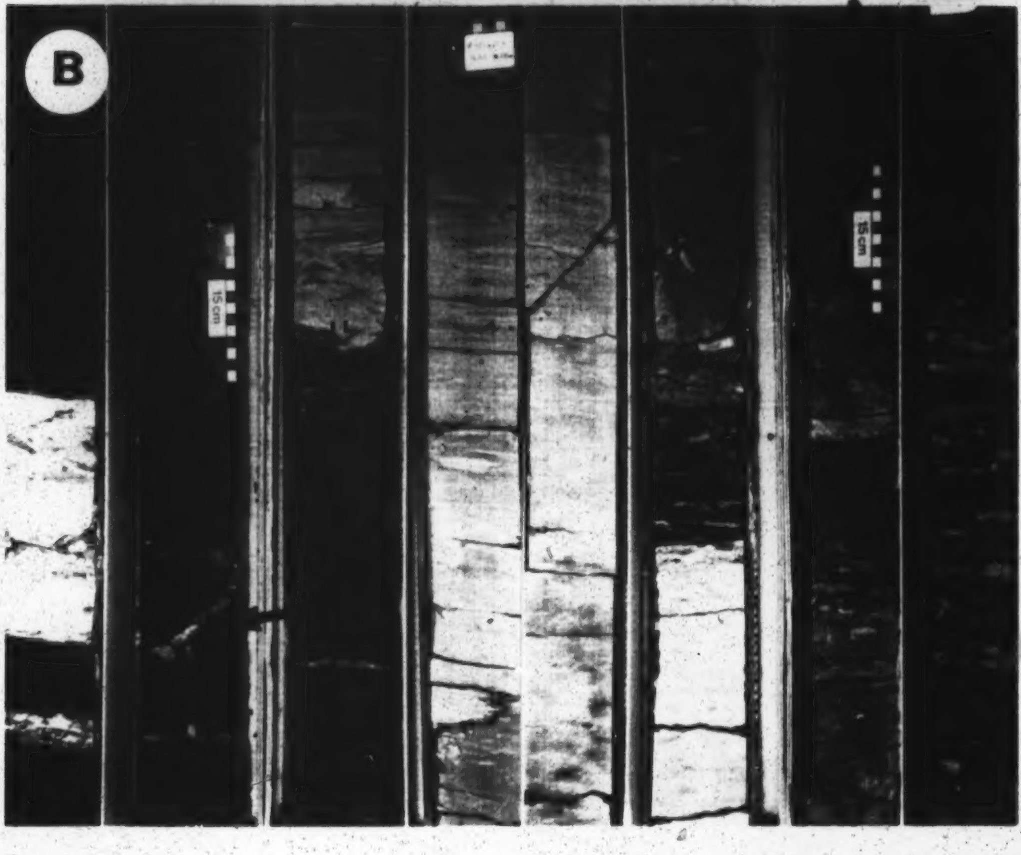
Facies Association 1 is restricted to the lowermost portions of the Grand Rapids Formation (GR_1 lithosome). It is represented by coarsening- and thickening-upwards successions of sandstone and mudstone. An idealized, complete succession begins with massive to bioturbate mudstones (Subfacies 1d; Fig. 4.1b) which are characterized by ichnofossil assemblages dominated by *Chondrites*, *Helminthopsis*, *Planolites* and *Zoophycos* (*Zoophycos* association). Stratigraphically upwards, the massive to bioturbated mudstones become interbedded with sharp-based, fining-upwards sandstone beds (Fig. 4.1a). Grain size is variable within these beds ranging from coarse- to fine-grained sandstone. Internally, the sandstone interbeds are typically massive, however, some beds display waning flow successions in which the massive sandstones grade upward into planar-laminations and culminate with small-scale wave ripple cross-stratification. The thickness and grain size of the sandstone interbeds typically increases upwards within the succession. The mudstone beds, particularly in the lower portions of the successions, are thoroughly bioturbated. Typically the relative degree of bioturbation

Figure 4.1
Facies Association 1

a) Cored sequence from the basal portion of the GR_1 lithosome. Sharp-based interlaminated mudstones (IM) from the base of a progradational shoreface succession. The mudstones are gradationally overlain by small-scale cross-stratified and planar laminated, slightly glauconitic sandstones (GS). Local calcite-cemented zones (CC) are common. Photograph is from 7-1-62-2W4, 402-408 m. Scale bar gradations are in centimeters.

b) Cored sequence illustrating the nature of the Clearwater Formation - Grand Rapids Formation contact (Hollow arrow points to the contact). The uppermost portion of the Clearwater Formation is comprised of planar-laminated and large-scale cross-stratified sandstones withn low diversity, low density ichnofossil asemblages dominated by *Zoophycos* (Zo). The basal portion of the Grand Rapids Formation is comprised of thoroughly bioturbated mudstones which are characterized by low diversity, high density ichnofossil assemblages dominated by *Chondrites*, *Helminthopsis*, *Planolites* and *Zoophycos*. The bioturbated mudstones are abruptly overlain by large-scale cross-stratified sandstone with abundant mudstone partings and intraclast. Photograph is from 9-35-62-3W4, 360-367 m. Scale bar gradations are in centimeters.


A
15 cm
15 cm
CC


B
15 cm
15 cm

decreases stratigraphically upwards within the mudstones. The sandstone beds are, for the most part, devoid of biogenic structures.

The interbedded sandstones and mudstones are overlain by a unit of medium- to fine-grained bioturbated sandstones (Facies 2). Characteristically these sandstones are devoid of well-preserved physical sedimentary structures and typified by a homogenized, bioturbate texture. These sandstones are characterized by high diversity, moderate density ichnofossil assemblages which may include the following: *Asterosoma, Bergaueria, Conichnus, Cylindrichnus, Macaronichnus, Planolites, Palaeophycus, Rhizocorallium, Rosselia, Skolithos, Teichichnus* and *Terebellina* (*Skolithos-Palaeophycus* association). The bioturbated sandstones, in turn, are overlain by a unit of medium- to fine-grained, low angle cross-stratified and planar-laminated sandstones (Facies 4 and 5). Generally, large-scale cross-stratification predominates in the lower portion, and planar-laminations in the upper portion.The intensity of bioturbation is typically very low in these sandstones, however, low diversity assemblages consisting of *Skolithos*, *Palaeophycus* and *Macaronichnus* have been observed.

Interpretations:

The coarsening- and thickening-upwards nature of this succession, combined with the association of physical and biogenic sedimentary structures, is interpreted to represent a progradational shelf to shoreface succession (Fig. 4.2). The basal bioturbated mudstones (Subfacies 1d) with their characteristic ichnofauna are interpreted to reflect the slow accumulation of hemipelagic mud in a quiet, stable shelfal setting. Observed ichnofaunal assemblages are dominated by structures generated by deposit-feeding organisms. Such ichnofossil assemblages are similar to ichnofossil assemblages representative of the *Zoophycos* or distal *Cruziana* ichnofacies. The sharp-based sandstone interbeds are interpreted to reflect the episodic emplacement of coarse-grained sediment below fairweather wave base by waning storm-induced flows in an otherwise quiescent offshore environment. The distinct absence of biogenic sedimentary structures within the sandstone

FACIES ASSOCIATION 1

COARSENING-UPWARDS SHELF-SHOREFACE SUCCESSIONS

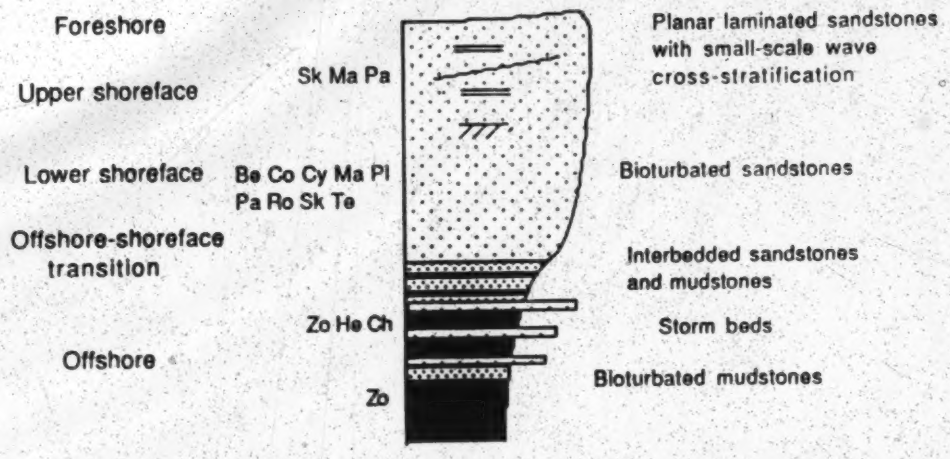

Foreshore
Upper shoreface
Lower shoreface
Offshore-shoreface transition
Offshore
Sk Ma Pa
Be Co Cy Ma Pl Pa Ro Sk Te
Zo He Ch
Zo
Planar laminated sandstones with small-scale wave cross-stratification
Bioturbated sandstones
Interbedded sandstones and mudstones
Storm beds
Bioturbated mudstones

Figure 4.2 Schematic representation of a typical coarsening- and thickening-upwards progradational shelf to shoreface facies succession. The major characteristics which distinguish this facies association from facies association 2 and 3 include: (1) ichnofossil forms characteristically associated with marine environments (*Chondrites* and *Zoophycos*); (2) increased diversity and density of ichnofossils relative to all other facies associations; and (3) the very high relative intensity of bioturbation which characterizes the shoreface sandstones. Refer to the legend in the appendix for an explanation of the symbols and abbreviations.

beds indicates the episodic, and rapid emplacement of the sandstone beds under high-energy conditions.

The overlying thickening-upwards successions of interbedded sandstones and mudstones is interpreted to represent the increasing frequency of storm event deposition associated with local shoreline progradation and deposition within a storm-influenced, offshore-shoreface setting. The overlying bioturbated sandstones are interpreted to represent lower shoreface deposits. The high relative intensity of bioturbation is indicative of prolonged periods of fairweather conditions which were interrupted by infrequent, higher-energy events. The high diversity of ichnofossils observed within these sandstones suggests that environmental conditions such as salinity, nutrient availability, oxygenation and substrate consistency, were optimal for the development of a stable benthic community of suspension- and deposit-feeding organisms. Optimal ecological conditions such as these are commonly observed in the lower shoreface environment (Howard, 1972; Howard and Frey; 1984; Frey and Howard, 1985).

The overlying planar-laminated and large-scale cross-stratified sandstones are interpreted to represent upper shoreface deposits. The large-scale cross-stratified sandstones reflect sediment transport in migrating dunes under the influence of asymmetrical oscillatory flows generated by shoaling waves. Interbeds of planar-laminated sandstone reflect higher-energy flow periods associated with storms. Overlying beds of planar-laminations are interpreted to represent swash-laminations produced in the foreshore subenvironment. Typically the upper portion of the sandstone unit is not developed, but appears to be truncated and abruptly overlain by fining-upwards successions of Facies Association 4.

4.1.2 Facies Association 2 (delta front deposits)

Description:

Facies association 2, like Facies Association 1, is characterized by coarsening- and thickening-upwards successions of sandstone and mudstone. A typical succession begins with a basal unit of dark to medium-grey, carbonaceous mudstones (Subfacies 1b). The lower 0.3 to 1.5 meters of this unit is typically massive and thoroughly bioturbated, and characterized by low diversity, high density ichnofossil assemblages dominated by *Teichichnus* (*Teichichnus* Association). Upwards within the carbonaceous mudstone unit, the relative degree of bioturbation decreases significantly. Also within this portion of the unit, the mudstones become increasingly well-laminated, and are typically arranged into distinct fining-upwards couplets of light-coloured laminated mudstone and dark-coloured massive mudstone. Evidence of biogenic reworking is sparse and restricted to the dark-coloured, massive mudstones. The high density *Teichichnus*-dominated ichnofossil assemblages are replaced by low density, low diversity ichnofossil assemblages dominated by *Planolites*. Syneresis cracks are particularly abundant within this portion of the mudstone unit. Thin, isolated lenses and interbeds of small-scale cross-stratified and massive sandstones become increasingly common towards the top of this unit.

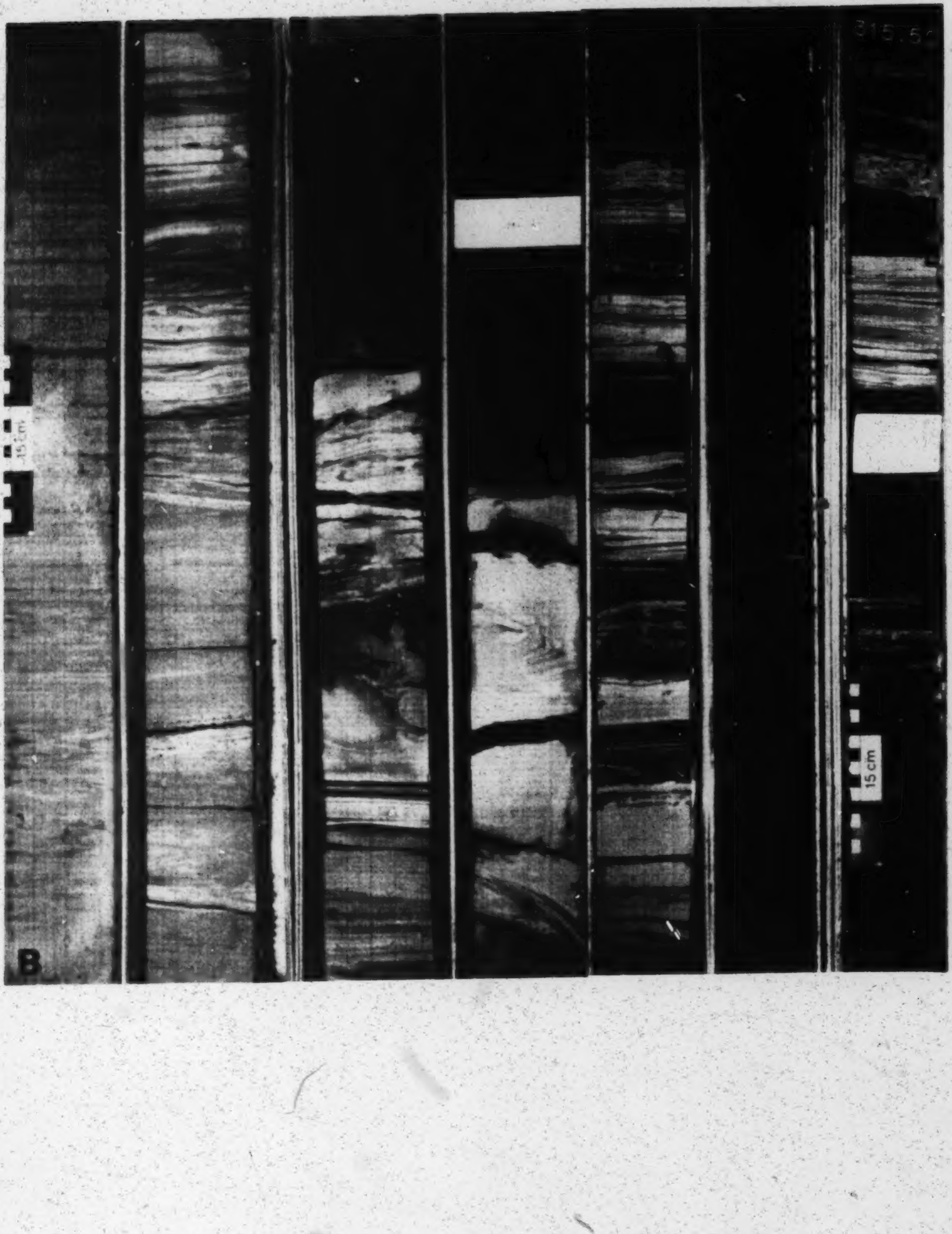
The interlaminated mudstones are gradationally overlain by a coarsening- and thickening-upwards succession of interbedded mudstones and small-scale current, wave and combined-flow ripple cross-stratified sandstones (Subfacies 7b). Typically, both current and combined-flow small-scale ripple cross-stratification is abundant in the lower portions, however, in the upper portion combined-flow small-scale ripple cross-stratification predominates. Stratigraphically-upwards the proportion of sandstone to mudstone increases, with sandstones beds becoming thicker and amalgamated. As within the underlying interlaminated mudstone unit, syneresis cracks are extremely abundant in the interbedded sandstones and mudstones. The relative intensity of bioturbation is typically low, although, locally it may be intense. This interbedded mudstone and sandstone unit is characterized by low diversity, low density ichnofossil assemblages dominated by *Planolites* and *Skolithos*.

The interbedded mudstone and sandstone unit is gradationally, although sometimes abruptly, overlain by a coarsening-upwards unit of large-scale cross-stratified and planar-laminated sandstone (Fig. 4.3). Grain size increases upwards within the unit, but this increase is subtle, increasing from very fine-grained to fine-grained sandstone. More readily apparent than the grain size change is the decrease in the mud-size fraction. The lower portion of this unit is dominated by argillaceous, small-scale wave and combined flow ripple cross-stratified sandstones with abundant mudstone drapes and thin mudstone interbeds. In addition to small-scale combined-flow ripple cross-stratification, planar laminations, flasers, lenticular and wavy bedding are common. Biogenic sedimentary structures are not abundant and tend to be restricted to the finer-grained or argillaceous portions of this unit. Low density, low diversity ichnofossil assemblages dominated by *Planolites* and *Skolithos* (*Skolithos -Planolites* and *Skolithos* associations) are common in the lower argillaceous portion of this unit. Typically, the relative degree of bioturbation decreases upwards within the unit as the overall proportion of mudstone decreases. The upper portion of this unit is dominated by large-scale cross-stratified and planar-laminated sandstones (Fig. 4.3). In addition to the overall upwards trend towards coarser grain sizes and better sorting, there is also a general decrease in the angle of cross-stratification. The uppermost portion of this unit is composed of well-sorted, low-angle, large-scale cross-stratified (Facies 4) and planar-laminated sandstones (Facies 5). Biogenic sedimentary structures, with the exception of rare isolated *Skolithos* and escape structures, were not observed within the upper portions of this unit. Carbonaceous debris is abundant within this unit, particularly in the uppermost portion, occurring both as disseminated matter and concentrated along bedding planes as thin laminae. Commonly, the planar-laminated sandstones which occur near the top of facies association 2 are root-penetrated and overlain by carbonaceous mudstones with thin argillaceous coal beds (Subfacies 1d).

Figure 4.3

Facies Association 2

Cored sequence from the upper unit of a Facies Association 2 coarsening- and thickening upwards succession. The lowermost 20 cm unit consists of small-scale cross-stratified sandstones which grade upwards into large-scale cross-stratified and planar-laminated sandstones with local interbeds of small-scale cross-stratified sandstones. This particular sequence is somewhat anomalous in that soft sediment deformation structures (convolute bedding, ball-and-pillow structures *etc.*) similar to those in the middle portion of the sequence are not typically encountered. The photograph from 15-17-61-3W4, 359-363 m (GR_3 lithosome). Scale bar gradations are in centimeters.


315.5
15 cm
15 cm
B

Interpretations:

The coarsening- and thickening-upwards facies successions which characterize facies association 2 are interpreted to record the progradation of a wave-influenced or fluvial-wave interaction deltaic complex into a shallow, brackish water basin (Fig. 4.4). The bioturbated mudstones which comprise the basal portion of the delta front successions are interpreted as prodeltaic mudstones. The thorough degree of bioturbation which characterizes this facies reflects slow suspension sedimentation, and an absence of significant coarse clastic input. The combination of abundant syneresis cracks and very low diversity ichnofossil assemblages are interpreted to be indicative of a marginal-marine depositional setting which was typified by fluctuating salinity. The overlying interlaminated mudstones with their distinct fining-upwards couplets record the incursion of sediment-laden deltaic plumes into the prodeltaic environment.

The interbedded mudstones and sandstones preserve the first evidence of significant coarse-grained sediment influx into the basin. The interbedded sandstones and mudstones are interpreted to represent transition zone deposits in which the physical and biological processes of the prodeltaic and lower delta front interdigitate. Sharp-based, small-scale cross-stratified sandstones record the periodic influx of sediment-laden storm- or flood-generated currents into an otherwise relatively quiescent body of water and are interpreted to represent delta front turbidites. In response to storms and/or floods sands were placed in suspension, transported to the prodelta, deposited from waning flows and subsequently modified by waves. Abundant syneresis cracks are indicative of fluctuating salinity conditions which are interpreted to be the result of high freshwater influx associated with flood conditions. During high river stages and floods the influx of abnormally high volumes of freshwater resulted in abrupt salinity reductions and induced the formation of syneresis cracks. Upwards within the succession, sandstone beds increase in both thickness and frequency reflecting the increasing frequency and intensity of higher-energy associated with progradation and shoaling-upwards.

FACIES ASSOCIATION 2

COARSENING-UPWARDS DELTA FRONT SUCCESSIONS

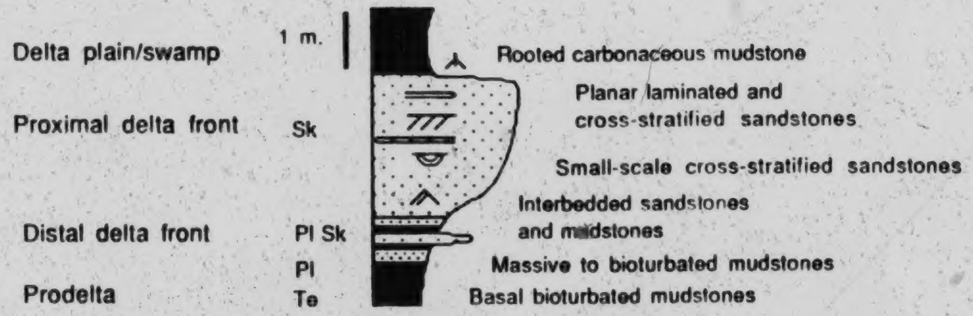

Delta plain/swamp
1 m.
Rooted carbonaceous mudstone
Planar laminated and
cross-stratified sandstones
Proximal delta front
Sk
Small-scale cross-stratified sandstones
Interbedded sandstones
and mudstones
Distal delta front
Pl Sk
Pl
Massive to bioturbated mudstones
Prodelta
Te
Basal bioturbated mudstones

Figure 4.4 Schematic representation of a typical coarsening- and thickening-upwards delta front succession which records delta progradation into a shallow, brackish water basin. Refer to the legend in the appendix for an explanation of the symbols and abbreviations utilized within the facies association diagrams.

The overlying package of cross-stratified and planar-laminated sandstone are interpreted to represent delta front deposits. The small-scale cross-stratified sandstones which predominate in the lower portion of this unit are interpreted to represent lower delta front deposits. The predominance of small-scale bedforms is suggestive of deposition under relatively low energy conditions. The small-scale cross-stratified sandstones are, for the most part, dominated by wave-generated structures and typically, lack current-generated structures. Abundant mudstone drapes within the lower portions of this unit indicate alternating suspension and traction deposition. This alternation of the depositional mechanism is interpreted to have been a result of current-velocity unsteadiness associated with tidal currents and/or fluctuating fluvial discharge. Similarly, thin interbeds of planar-laminated sandstone within the lower portion of this unit probably reflect sediment emplacement by episodic, high energy events associated with storm-surge flows, floods or density flows. The overlying large-scale cross-stratified and planar-laminated sandstones are interpreted to represent upper delta front deposits. The predominence of large-scale cross-strata and planar-laminations in the upper portions of this unit reflects increasing wave-induced sediment transport associated with shoaling and breaking waves. The large-scale cross-stratified sandstones reflect sediment transport in migrating dunes under the influence of asymmetrical oscillatory flows generated by shoaling waves. Overlying beds of planar-laminations reflect higher-energy flow periods associated with storms. The near dearth of preserved biogenic sedimentary structures is consistent with a relatively high energy depositional setting with a shifting particulate substrate.

The overlying rooted, carbonaceous mudstone horizon reflects emergence and establishment of peat-forming swamps or marshes. Mudstone beds with high densities of rootlets are suggestive of a heavily vegetated, well-developed coastal plain. The uniform distribution of this horizon indicates that these peat horizons or mats had exceptional areal extent, potentially covering the entire delta lobe. This horizon is interpreted to represent the regressive maximum and records the termination of progradational deltaic sedimentation and abandonment of the deltaic complex. Once sediment supply to the deltaic shorelines ceased, and subsequently progradation was arrested, vegetation could develop on the emergent delta platform. As such, this horizon defines an inflection point which separates regressive deltaic sedimentation from delta abandonment and transgression. Peat-formation or carbonaceous mudstone deposition continued until the rate of accumulation did not exceed or equal the rate of relative sea level rise. At this point the broad, shallow delta platform would be submerged by slowly rising brackish waters.

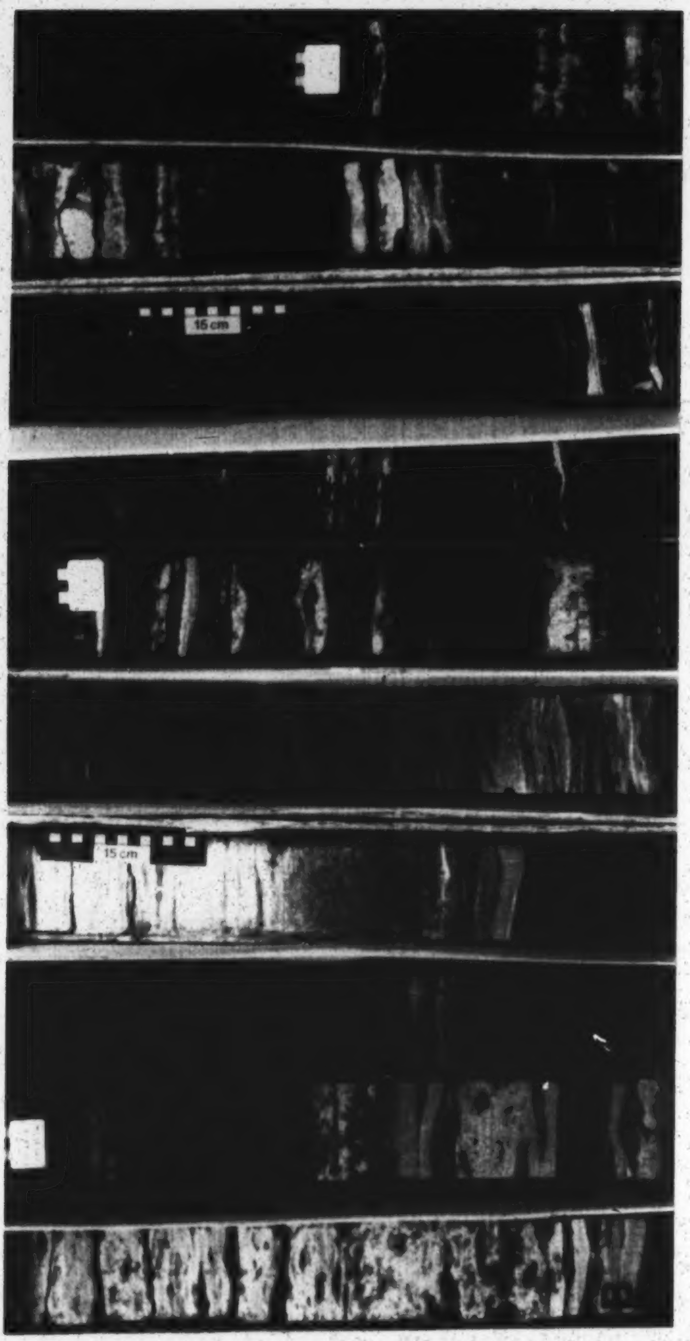
4.1.3 Facies Association 3 (bay-fill/delta plain deposits)

Description:

Facies association 3 comprises coarsening-upwards facies successions of sideritic mudstones and sandstones (Fig. 4.5). In contrast to the delta front successions the coarsening-upwards successions of facies association 3 exhibit considerable variation in lithology, grain size, geometry and cumulative thickness. Each succession begins with a thick lower unit in which the dominant lithology is sideritic mudstone (Subfacies 1c) with rare thin (0.5-3 cm) interbeds of small-scale cross-stratified and planar-laminated sandstone. Siderite concretions, syneresis cracks and soft sediment deformation structures are common accessory features of the interlaminated mudstones. Ichnologically, the mudstone beds are characterized by low diversity ichnofossil assemblages dominated by *Planolites*. This lower succession of bioturbated and interlaminated mudstones may constitute the entire bay-fill succession. In contrast, in the eastern portion of the study area (Twps. 60, 61 and 62, Rge. 1W4) the mudstones are gradationally overlain by thin (1-4 m), coarsening- and thickening-upwards units of cross-stratified and planar-laminated sandstone. The lower portion of this sandstone-dominated unit consists of thickening-upwards units of very fine- to fine-grained, carbonaceous, small-scale current and combined flow ripple cross-stratified sandstone (Facies 3) with thin mudstone drapes and interbeds. The mudstone drapes and interbeds are abundant with the lower portion of this unit but decrease upwards within the succession. Bioturbation is highly variable within this unit, ranging from sparse to locally intense. Recognized ichnofossil include *Skolithos*, *Cylindrichnus*, *Gyrolithes*, *Planolites*, *Rosselia*, *Bergaueria* ? and *Palaeophycus*?.

Figure 4.5
Facies Association 3

Cored sequence illustrating two stacked coarsening-upwards successions of Facies Association 3. The base of each coarsening-upwards succession consists of massive to interlaminated mudstones. Upwards the mudstones are overlain by a coarsening upwards unit of interbedded laminated mudstones and small-scale cross-stratified sandstones. Upwards within the successions the interbedded sandstones and mudstones are overlain by a unit of small-scale cross-stratified and planar-laminated mudstones. The photograph is from 12-15-62-4W4, 348-356 m (GR_5 lithosome). Scale bar gradations are in centimeters.


15 cm
15 cm

Generally these ichnofossils occur in very low diversity, low density assemblages. As well, there also appears to be a number of nondescript disrupted fabrics of ?plant origin. Carbonaceous debris is very abundant within the small-scale cross-stratified sandstones and it occurs as thin, vertically-oriented filaments or rootlets, carbonaceous laminae and as disseminated matter.

The thickening-upwards units of small-scale current and combined-flow ripple cross-stratified sandstone typically grade upwards into planar-laminated (Facies 5) and locally, low-angle, large-scale cross-stratified sandstones (Facies 4). In the uppermost portions of this unit, many of the planar-laminated sandstone beds possess thin caps of wave ripple cross-stratification. Mudstone drapes while abundant in the lower portion, are uncommon in the upper portions. Evidence of biogenic reworking is localized into discrete horizons that are pervasively bioturbated with a unique ichnofossil assemblage, consisting predominantly of *Gyrolithes* (*Gyrolithes* association). Bioturbated and non-bioturbated, cross-stratified or planar-laminated units are interbedded on a decimeter to meter scale. Typically, the uppermost planar-laminated sandstones are poorly sorted, micaceous, rooted and have a bleached appearance. The coarsening-upwards successions generally terminate with a fining-upwards succession of silty mudstones, carbonaceous mudstone (Subfacies 1d) and thin argillaceous coal beds, similar to the horizons which culminate the delta front successions (facies association 2).

Interpretations:

The coarsening- and thickening-upwards successions of mudstones and sandstones, which characterize Facies Association 3, are interpreted to record the progressive in-filling of shallow, brackish water bays (Fig. 4.6). The basal bioturbated mudstones reflect slow deposition of organic-rich muds in relatively shallow, brackish water interdistributary bays. The high density of ichnofossils observed within this horizon suggests a marine influence, however, the extreme low diversity of ichnofossils suggests that the bays were not fully saline and were charactized by high freshwater input. The

FACIES ASSOCIATION 3

COARSENING-UPWARDS BAY-FILL SUCCESSIONS

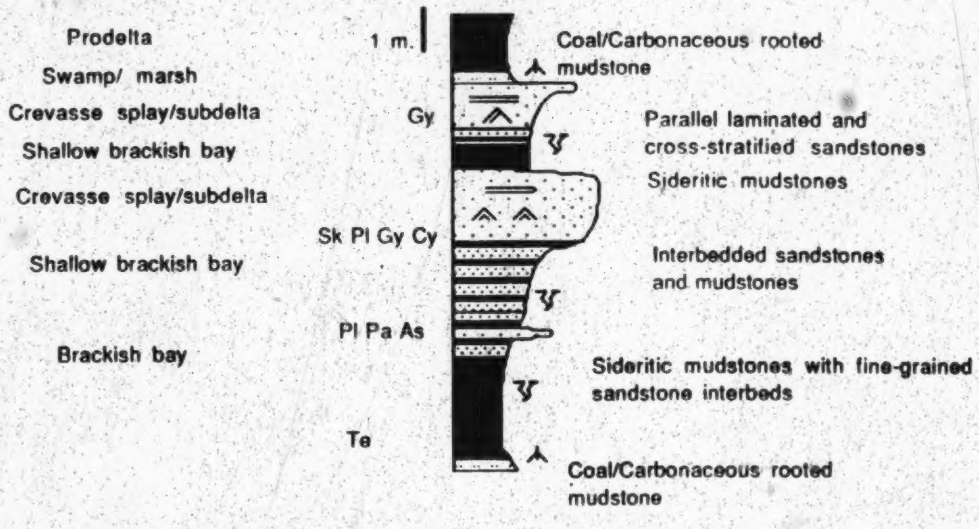

Prodelta
Swamp/ marsh
Crevasse splay/subdelta
Shallow brackish bay
Crevasse splay/subdelta
Shallow brackish bay
Brackish bay
1 m.
Gy
Sk Pl Gy Cy
Pl Pa As
Te
Coal/Carbonaceous rooted mudstone
Parallel laminated and cross-stratified sandstones
Sideritic mudstones
Interbedded sandstones and mudstones
Sideritic mudstones with fine-grained sandstone interbeds
Coal/Carbonaceous rooted mudstone

Figure 4.6 Schematic representation of a typical coarsening- and thickening-upwards bay-fill deposit which records the progressive in-filling of a shallow, brackish water bay with sediment. Refer to the legend in the appendix for an explanation of the symbols and abbreviations utilized within the facies association diagrams.

overlying interlaminated mudstones with thin sandstone interbeds records the periodic influx of sediment-laden currents into the interdistributary bays and the superposition of flood- and storm-related sedimentation upon background, fairweather or inter-flood mud deposition.

The upper coarsening- and thickening-upwards packages of sandstone are interpreted to record the later stages of the bay-fill cycle in which crevasse splay and crevasse channel sands coalesced, forming , locally, sheet-like sandstone bodies. The coarsening- and thickening-upwards nature of the sandstones reflects increasing energy conditions as the sedimentation surface shoaled because of the progressive infilling of the bay with sediment. The abundance of carbonaceous mudstone drapes and partings within the cross-stratified sandstones and the cyclic nature of their occurrence suggests that the bays had an open connection with the sea. The repetitive, and potentially rhythmic occurrence of these mudstone drapes is interpreted to reflect current velocity fluctuations associated with tidal currents. Within the upper portions of the bay-fill succession, evidence of wave reworking becomes more prevalent. Reworking of the crevasse-supplied sediment by wind- or storm-generated waves is reflected in the wave-rippled bed tops of the planar-laminated sandstones which occur near the top of the coarsening-upwards successions. Typically, the lower portions of the bay-fill successions record the interaction of fluvial and tidal currents, with only minor evidence of wave reworking, whereas the upper portions are characterized by tidal- and wave-dominated processes. Thus, from a hydrodynamic point of view, the depositional environment was characterized by a complex interaction of unidirectional fluvial- and tide-generated currents, combined flow and oscillatory currents.

The rooted, carbonaceous mudstones and thin coals which cap the bay-fill cycles suggest that several splay sandstones coalesced to form an extensive surface upon which peat swamps developed, subsequently filling the entire interdistributary area. This horizon also records the termination of the bay-fill cycle as a result of a relative sea level rise. The bay-fill cycle terminated when sedimentation no longer exceeded the rate of subsidence. At this point the delta plain muds and peats became submerged and were transgressed by brackish waters. Termination of the bay-fill cycle is interpreted to have occurred in response to a decrease in the sediment influx into the depositional basin which was a consequence of the upstream abandonment of a distributary channel complex.

These cyclic bay-fill deposits are very similar to interdistributary bay deposits documented from modern and ancient shoal-water deltaic settings (Elliot, 1974; 1986; Horne *et al.*, 1978; Coleman and Prior, 1980). Similar cyclic bay-fill deposits have been documented by Wightman *et al.* (1987) from correlative Mannville Group strata in the Lloydminster area.

4.1.4 Facies Association 4 (distributary channel-fill deposits)

Descriptions:

Facies association 4 comprises sharp-based, fining-upwards successions of sandstone and mudstone. The fining-upwards successions of facies association 4 exhibit considerable degrees of variation in composition and thickness (8 to 40 m). However, each fining-upwards facies succession can be considered to be comprised of three units: (1) a lower, sandstone-dominated unit; (2) a middle heterolithic unit; and (3) an upper mudstone-dominated unit.

Typically, the base of the lower, sandstone-dominated unit is defined by a zone of concentrated mudstone clasts which is overlain by a matrix-supported intraformational conglomerate or breccia consisting of subrounded to angular siderite-cemented mudstone intraclasts supported in a matrix of medium- to fine-grained massive sandstone (Facies 6). The remainder of the sandstone-dominated unit consists of a fining-upwards succession of medium- to fine-grained, planar-laminated, massive, large- and small-scale cross-stratified sandstones (Facies 3 and 4; Fig. 4.7a and b). In some cores, the bulk of the lower unit is

Figure 4,7

Facies Association 4

Four core photographs illustrating the major elements of the fining-upwards successions which comprise Facies Association 4. The majority of the fining-upwards successions recognized within the Grand Rapids Formation are consist of:

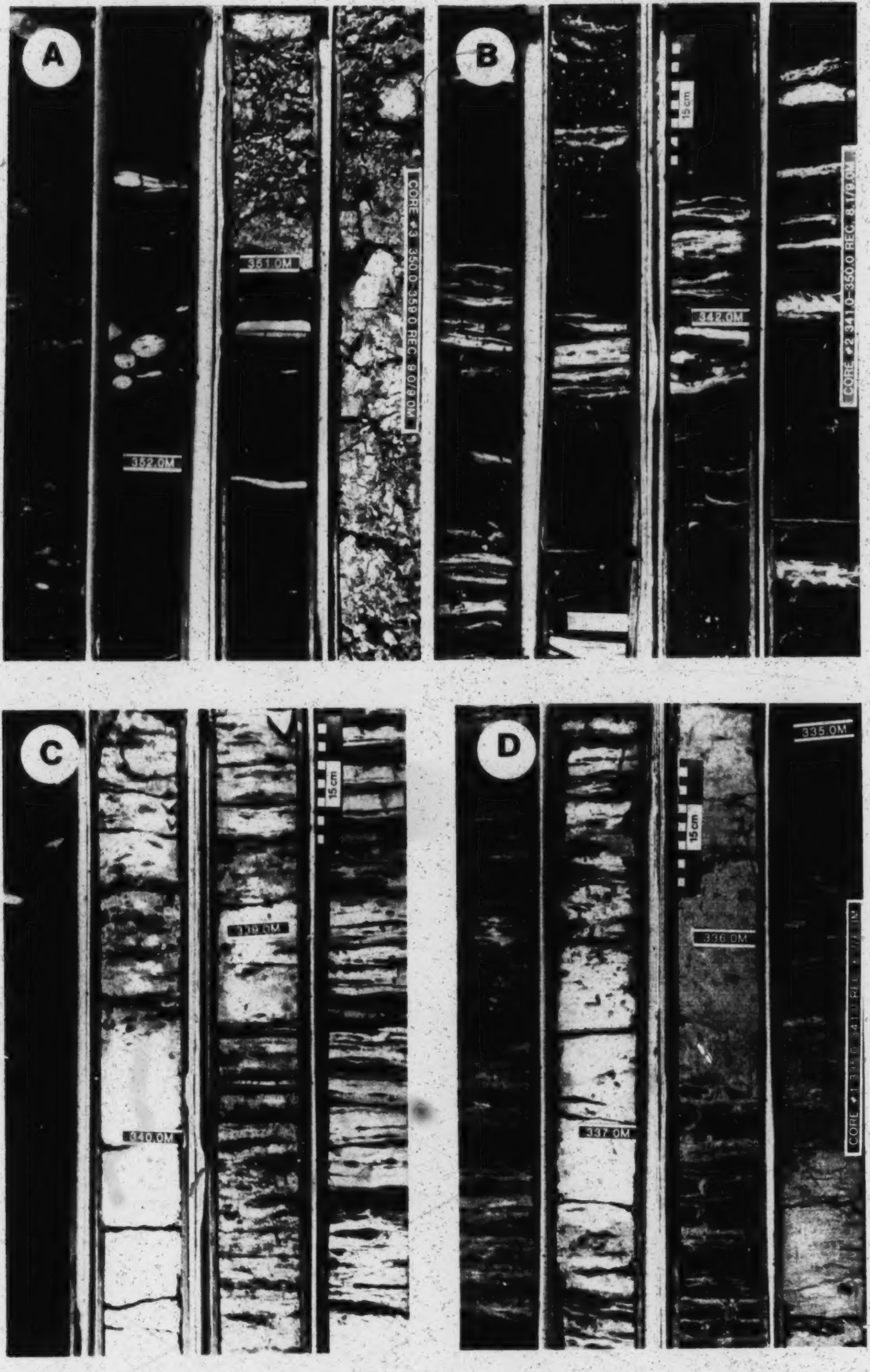
a) A lower sandstone-dominated unit comprising of massive andplanar-laminated sandstones with abundant mudstone intraclasts.

b) The upper portion of this sandstone-dominated unit is made up of large- and small-scale cross-stratified sandstones with abundant mudstone partings and drapes. Upwards within this unit, the sandstones typically become finer-grained, argillaceous, decrease in set thickness and are dominated by small-scale cross-stratification.

c) A middle, heterolithic unit consisting of interbedded sandstones and mudstones. Typically, the sandstone beds thin upwards while the mudstone beds thicken, however, the high degree of bioturbation obscures much of the bedding in the lower unit. The interbedded mudstone and sandstones are characterized by low diversity ichnofossil assemblages comprised of *Planolites* and *Skolithos*.

d) An upper mudstone-dominated unit which comprises massive to bioturbated mudstones with abundant carbonaceous debris, carbonized rootlets and coal clasts. Soft sediment deformation structures such as convolute bedding,slickensides and microfaults are common accessory features encountered within the mudstone-dominated unit.

The photographs are from 7-20-63-3W4, 335-354 m (GR_1 lithosome). Scale bar gradations are in centimeters.


A
352.0M
351.0M
CORE #3 350.0-359.0 REC 9.0/9.0M
B
15cm
342.0M
CORE #2 341.0-350.0 REC 8.1/9.0M
C
15cm
339.0M
340.0M
D
335.0M
15cm
336.0M
337.0M
CORE #1

composed of alternating planar-laminated (Facies 5) or low-angle cross-stratified sandstone (Facies 4) and massive sandstone (Facies 6). Angular to rounded sideritic mudstone clasts are abundant within the massive sandstones (Fig. 4.7a), locally comprising 70 percent of a particular bed. Mudstone drapes and thin mudstone interbeds are commonly found mantling foreset and bottomset laminae in the small- and large-scale cross-stratified sandstone beds (Fig. 4.7b). Typically, the frequency, thickness and abundance of mudstone drapes increases upwards within the unit. The lower, sandstone-dominated unit is, for the most part, devoid of biogenic sedimentary structures. Some low diversity ichnofossil assemblages dominated by *Planolites* and *Skolithos* (*Skolithos -Planolites* association) were observed within the mudstone drapes and interbeds.

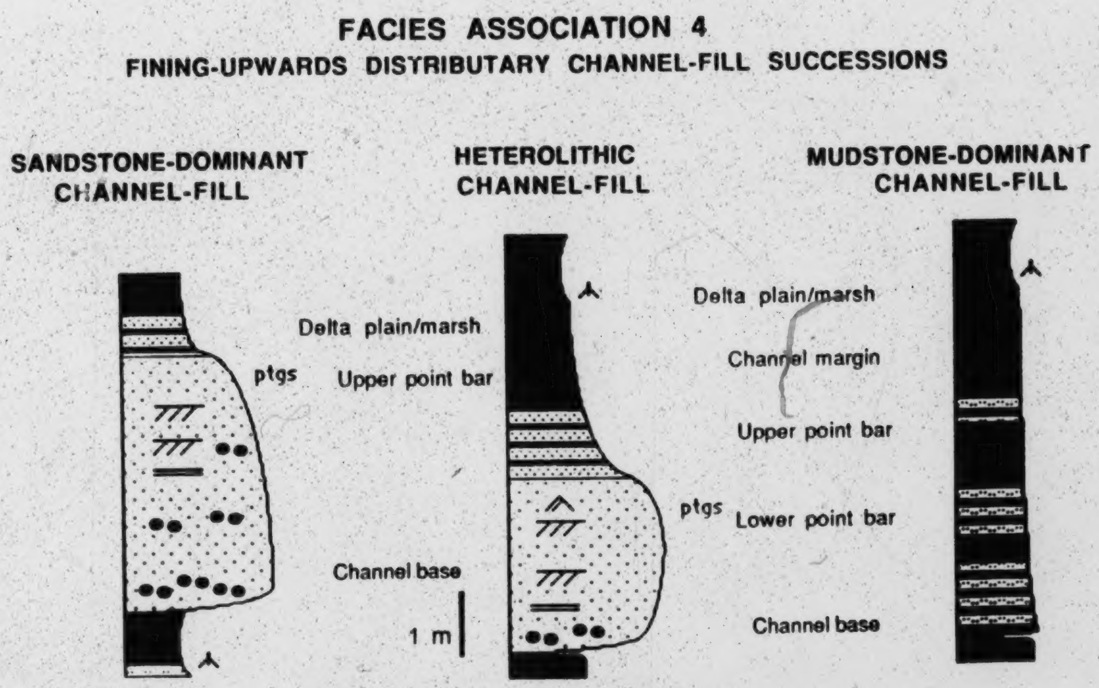
The middle, heterolithic unit consists of a fining-upwards succession of mm- to cm-scale intercalated fine-grained sandstone and massive to bioturbated mudstone (Subfacies 7a and 7b; Fig. 4.7c and d). Internally, the cm-scale sandstone beds are characterized by small-scale current ripple cross-stratification and less commonly, by large-scale cross-stratification, while the mm-scale beds are typically massive. The mudstone beds tend to be poorly-laminated and bioturbated or massive in appearance. Other sedimentary structures observed within the middle unit include lenticular, wavy and flaser bedding. Unlike the lower, sandstone-dominated unit, bioturbation may be intense in the interbedded sandstones and mudstones (Fig. 4.7d). Recognized ichnofossils include *Cylindrichnus*, *Gyrolithes*, *Planolites* and *Skolithos*.

The upper mudstone-dominated unit is characterized by massive to bioturbated mudstones (Subfacies 1c and 1d) with abundant carbonaceous debris, rootlets and coal clasts in the upper portions (Fig. 4.7d). Bioturbation is extremely variable within the upper unit. Typically, the relative intensity of bioturbation decreases as the carbonaceous content of the mudstones increase. On the other hand, the relative intensity of bioturbation increases as the silt content of the mudstones increases. Convolute bedding, slickensides, microfaults and other soft sediment deformation structures are commonly observed within this unit. Many of the fining-upward successions of Facies Association 4 terminate with a rooted, carbonaceous mudstone or argillaceous coal horizon (Fig. 4.7d).

Interpretations:

The sharp-based, fining-upwards successions of sandstone and mudstone which characterize facies association 4 are interpreted to represent distributary channel-fill deposits (Fig. 4.8). The overall fining-upwards trend of decreasing sediment size and bedform scale of the lower unit reflects lateral migration and/or abandonment of distributary channels. The basal contacts of the channel-fill successions are interpreted to represent erosional lag deposits and intraformational breccias/conglomerates indicating that channel deposition commenced with incision into strata. The fining-upwards stratification sequence of massive and planar-laminated sandstone, large-scale cross-stratified sandstone and small-scale cross-stratified sandstone represents a progressive decrease in flow velocity. This decrease in flow velocity may have been gradual or abrupt, and may have occurred in response to lateral migration, abandonment or seasonal discharge fluctuations. Regardless of the process responsible the sedimentological response will result in a similar, overall fining-upwards trend of grain size and bed form scale. Repetition of lithology and erosional surfaces within the successions suggests that not all of the channels can be characterized by a simple, single storey fining-upwards succession. Instead some of the channel-fill deposits appear to have undergone a complex history of incision, establishment, abandonment and reactivation.

Interbedded sandstone and mudstones of the middle, heterolithic unit are interpreted to represent lateral accretion deposits produced within tidally-influenced channels. The dominant feature of this unit is the rhythmic intercalation of sandstone and mudstone into horizontal to inclined sets or couplets. These inclined sets of interbedded sandstone and mudstone in the middle unit resembles epsilon cross-stratification (ECS) of Allen (1963) or a recently described variation of ECS termed inclined heterolithic stratification (IHS) described by Thomas *et al*. (1987). Bedding units of ECS or IHS typically consist of inclined layers of two or more lithologies which may be internally graded or arranged into



FACIES ASSOCIATION 4

FINING-UPWARDS DISTRIBUTARY CHANNEL-FILL SUCCESSIONS

Figure 4.8 Schematic illustration of typical sharp-based, fining-upwards channel deposits. A continuum of channel-fill types ranging from sandstone-dominant to mudstone-dominated channel-fills are present within the Grand Rapids Formation. Sandstone-dominant and heterolithic channel-fills are most frequent types encountered. Typically the channel-fill successions are characterized by: (1) fining-upwards of grain size and bedform scale; (2) a progressive increase in the relative intensity of bioturabation upwards; (3) an increase in both the diversity and density of ichnofossils; and (4) an increasingly strong signature of tidal processes upwards within the channel-fill succession. Refer to the legend in the appendix for an explanation of the symbols and abreviations utilized within the diagram.

distinct coarse- and fine-grained beds that together constitute an individual couplet (Allen, 1963; 1970; Thomas *et al.*, 1987). ECS or IHS has been interpreted to be produced by lateral accretion upon point bar surfaces in tidally-influenced channels (Allen, 1963; 1970; Barwis, 1978; Clifton, 1983; Thomas *et al.*, 1987). This rhythmic intercalation of sandstone and mudstone reflects regular alternations in the depositional mechanism. Currents regularly alternated between those capable of transporting sand in migrating large- and small-scale bedforms and those below the threshold for tractional sediment transport. Suspension settling of mud and biogenic reworking dominated during these later periods. Periods of tractional sediment transport were intermittent and restricted to short durations, possibly associated with peak current velocities during spring tides or during longer term seasonal current velocity fluctuations. Van den Berg (1981) has interpreted a succession of interbedded sandstone and mudstone from an abandoned channel-fill from the Oosterschelde to be a product of seasonal-scale fluctuations of current velocity. The sandstone beds reflect periods of significant sediment transport during winter storms, whereas the mudstone beds reflect the predominance of mud deposition during quiescent summer months. The scale of interbedding in the middle unit, mm- to cm-scale, suggests an overall lower-energy setting than that interpreted for the lower, sandstone-dominated unit. It appears that the low energy flow conditions were of longer duration. In otherwords, the higher-energy events appear to have been reduced in magnitude, but occurred on a more regular basis. The high relative intensity of bioturbation within the middle unit also suggests that intervals of sediment transport were reduced in both duration and intensity. Homogenized sandy mudstone beds indicate that slack water periods were of sufficient duration to facilitate the thorough biogenic intermixing of the mudstone and sandstone beds. The high density, low diversity ichnofossil assemblages which characterize this unit are supportive of a low to moderate energy, brackish water setting.

The carbonaceous mudstones of the upper unit are interpreted to represent vertical aggradation deposits that recorded the final stages of the channel abandonment process. Abundant syneresis cracks and the low diversity ichnofossil assemblages within the carbonaceous mudstones are indicative of a distinct, but diminished marine influence.

However the dramatic decrease in both diversity and density of ichnofossils suggests that environmental stresses, such as low and/or variable salinity or reduced oxygen levels significantly influenced the nature of the benthic community. Very few species had the ability to tolerate the extreme environmental stresses that appear to have been present during deposition of this unit. Siderite concretions and siderite cemented zones are consistent with the rapid accumulation of mud and the decomposition of organic matter within a restricted, brackish water setting (Gautier, 1982).

4.2 Depositional History of the Grand Rapids Formation

As previously mentioned, the Grand Rapids Formation can be subdivided into six flooding surface bounded depositional units termed lithosomes. Each lithosome records an interval of deltaic sedimentation within the study area. Internally each lithosome is characterized by a predictable vertical and lateral succession of facies. These facies are arranged into one of the recurring facies associations discussed in the preceding portion of this chapter. The following discussion brings together all lines of evidence presented in the preceding chapters to interpret the depositional history of each lithosome and the Grand Rapids Formation as a whole.

From the preceding discussion it appears that, for the most part, the Grand Rapids Formation reflects deposition within a deltaic setting. A number of recurring features within the Grand Rapids Formation are suggestive of a deltaic setting; the most significant of these include:

(1) the ichnological signature of fluctuating brackish water conditions;
(2) the abundance of carbonaceous debris, and particularly the occurrence of rooted, carbonaceous mudstone horizons capping shoaling-upwards successions; and
(3) the physical sedimentological evidence for the interaction of waves, tidal currents and fluvial currents.

The GR_1 lithosome records a single progradational cycle across a very low gradient shelf following a widespread transgressive event which terminated the deposition of the Clearwater Formation. The lowermost portion of the GR_1 lithosome comprises a progradational, storm-dominated shoreface succession (Facies Association 1). Physical and biogenic sedimentary structures reflect persistent wave action and periodic intense storms. Sediment entering the depositional basin was rapidly transported along shore and reworked into a series of beach deposits which fronted a progradational shoreface or wave-dominated delta front complex. Thoroughly bioturbated mudstones at the base of the progradational shoreface successions which preserve well-developed, diverse ichnofaunal assemblages suggests that marine, or near fully marine conditions existed at the onset of deposition of the GR_1 lithosome.

The progradational shoreface deposits of Facies Association 1 are erosively overlain by distributary channel-fill deposits of Facies Association 4 (Fig. 4.9). Throughout most of the study area the channels have incised into and removed a considerable portion of the underlying progradational shoreface successions. Internally, the channel-fill deposits display a number of features, such as thin mudstone drapes and partings, which occur in a regular and repetitive manner suggesting deposition under the influence of tidal currents. A marginal marine or brackish water depositional setting is also suggested by the nature of the ichnofaunal assemblages preserved within the channel-fill deposits. A distinct, yet diminished marine influence is suggested by the low diversity, low density ichnofossil assemblages (*Planolites* association), particularly within the upper portions of the channel-fill deposits. This pattern of wave-dominated shoreface deposits and tide-influenced channel-fill deposits is very similar to the distribution of depositional environments observed on many modern wave-influenced or wave-tide interaction coastlines such as the Niger (Oomkens, 1974; Allen, 1968) and Rhône (Oomkens,1967) deltas. In such settings the interdistributary areas are characterized by wave-dominated processes while the distributaries may experience considerable tidal and/or fluvial activity.

GR$_1$ LITHOSOME
PALEOENVIRONMENTAL RECONSTRUCTION

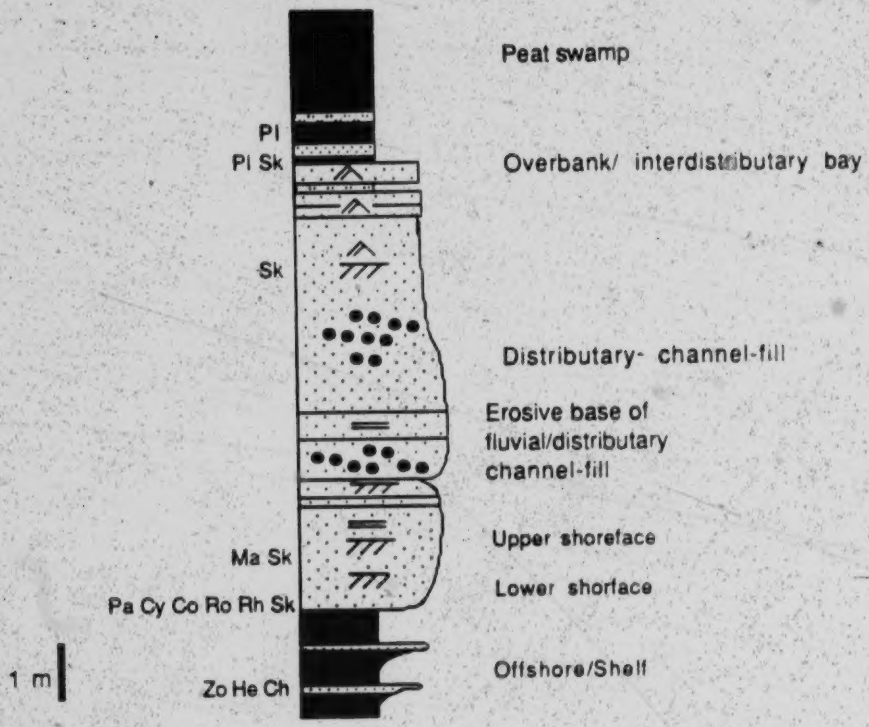


Fig. 4.9 Paleoenvironmental reconstruction of the GR$_1$ lithosome. Typically the lower portion of the GR$_1$ lithosome is comprised of a progradational shoreface succession which is erosively overlain by fluvial or distributary channel-fill deposits. Physical and biogenic sedimentary structures suggests that the channels were influenced by tidal currents. Some of the channel-fill successions exceed 40 meters in thickness. Refer to the appendix for an explanation of the symbols and abbreviations utilized in this diagram.

Carbonaceous, rooted mudstones (Subfacies 1d) which gradationally overlie the distributary channel-fill deposits are interpreted to record the abandonment of the distributaries and the local establishment of peat-forming swamps in response to rising relative sea level. The term relative sea level, in the context of this discussion, is used to refer to the combined effects of changes in sediment supply, eustatic sea level and the rate of subsidence or other tectonic mechanisms. An increase in the rate of relative sea level rise resulted in flooding, shoreline retreat and non-deposition. Once sediment supply to the deltaic shorelines ceased and, subsequently progradation was arrested, vegetation could develop on the emergent delta platform. Peat and carbonaceous mud accumulation continued until the rate of aggradation could no longer keep pace with subsidence. At this point the broad, shallow delta platform was submerged.

Following this depositional hiatus, thoroughly bioturbated mudstones (Subfacies 1b) of the basal GR_2 lithosome were deposited in the quiet, shallow water bays which developed on top of the submerged GR_1 lithosome delta plain deposits. The contact between the uppermost carbonaceous rooted mudstone of the GR_1 lithosome and the basal bioturbated mudstones of the GR_2 lithosome defines the transgressive flooding surface which separates the GR_1 lithosome and GR_2 lithosome.

The low diversity and density of ichnofossils observed within the basal GR_2 lithosome mudstones suggests that marine conditions similar to those interpreted to have existed at the onset of GR_1 lithosome deposition apparently did not develop. The thorough degree of biogenic reworking which characterizes this facies requires physical and ecological stability, suggesting that these brackish water environments were created by slowly rising waters and that these environments existed for a sufficient period of time to facilitate the development of a relatively stable benthic community. This change in relative salinity between the deposition of the GR_1 and GR_2 lithosomes may be related to a change in the magnitude of the relative sea level rise, configuration of the depositional basin, an increase in fluvial input or an increase in the volume of sediment supplied to the depositional basin.

The GR_2 lithosome is characterized by small-scale coarsening-upwards facies successions which record the progradation of a wave-influenced or fluvial-wave interaction delta complex into a shallow, brackish water basin (Fig. 4.10).Rapid vertical and horizontal facies transitions characteristic of fluvial-dominated systems have not been observed. Rather the delta front successions observed within the GR_2 lithosome, and GR_3 lithosome (see following discussions) are laterally and vertically homogeneous and dominated by wave-generated or wave-influenced physical sedimentary structures. This vertical and lateral facies continuity within the delta front successions suggests that sediment deposited in the vicinity of the distributary mouths was reworked by persistent wave action. It is suggested that the low gradient of the depositional shelf and the shallow depth of the depositional basin controlled the pattern and thickness to which the delta front succession developed.

Locally, distributary channels have incised into the delta front sandstones. Incision of the distributary channels into the delta front deposits is interpreted to have occurred in response to autocyclic processes inherent within the delta complex; specifically, progradation and channel switching. With progressive progradation of a delta, distributary channel systems develop unstable gradients. Eventually, the distributary channel system, in response to this unstable gradient and overextension, will divert across the delta plain to a shorter and steeper-gradient route to the shoreline (Frazier, 1967; Coleman and Wright, 1975). Eventually this new distributary will divert more and more of the flow, until the original distributary, no longer capable of supplying sediment to the delta, is abandoned. Downstream, the delta because of sediment starvation, will abandon, subside and eventually become transgressed.

The initiation and abandonment of deltaic lobes or complexes is related to the frequency of channel avulsion. In fluvial-dominated systems, because the deltas are local features and distributaries are abundant, progradation is rapid, unstable gradients develop

GR_2 LITHOSOME
PALEOENVIRONMENTAL RECONSTRUCTION

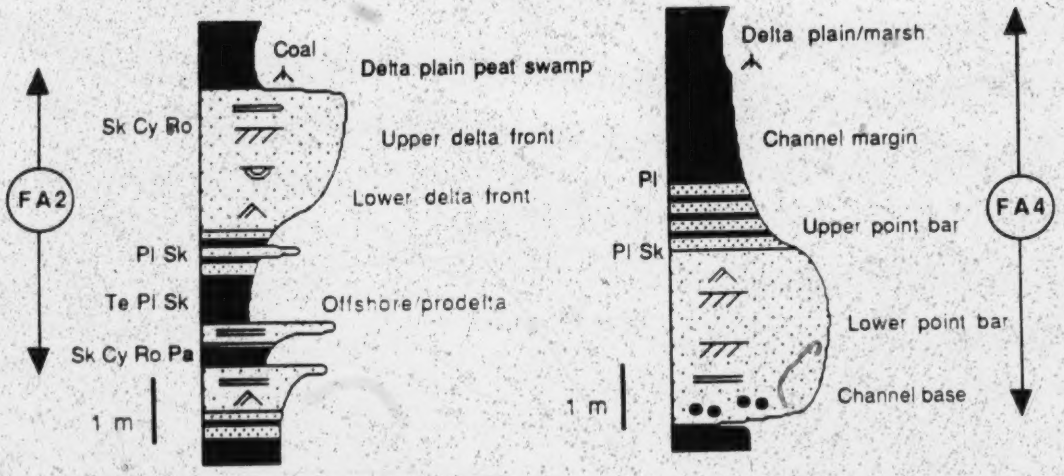


Fig. 4.10 Paleoenvironmental reconstruction of the GR_2 lithosome. Throughout most of the study area, the GR_2 lithosome comprises a single progradational delta front succession. In the northern portion of the study area a second coarsening upwards succession has been recognized. In some areas, tidally-influenced distributary channel-fill deposits have incised into and replaced the delta front deposits. Refer to the legend in the appendix for an explanation of the symbols and abbreviations utilized in this figure.

readily and, therefore, avulsion occurs frequently and lobes proliferate. However, in wave-dominated systems progradation occurs more slowly over an extensive delta front, therefore, avulsion is less frequent. Furthermore, a large proportion of the delta lobe would be reworked, and potentially, the entire delta lobe could be reworked. Therefore, channel switching is a process which preferentially operated in fluvial-dominated and fluvial-wave interaction delta systems (Elliot, 1986).

Typically, the GR_2 lithosome culminates with a rooted carbonaceous mudstone horizon indicating that delta lobe abandonment was accompanied by widespread marsh development. However, rarely the GR_2 lithosome terminates with a poorly-sorted, fine- to medium-grained, bioturbate muddy sandstone horizon (Facies 2). These bioturbated muddy sandstones are interpreted to be transgressive deposits and record the erosion and reworking of the delta front sands following abandonment of the delta lobe/complex. As such, these coarse-grained transgressive deposits may represent remnants of a transgressive barrier island arc (*cf.* Penland et al., 1988) described from the modern Mississippi Delta. The limited distribution of this type of transgressive deposit suggests that erosion and reworking was restricted to the most seaward portions of the delta complex and such transgressive barriers were not well-developed in the study area. Rather, it appears that the majority of the delta complex was protected by the overlying, widespread peat horizon. The broad, low relief of the delta plain effectively attenuated wave energy such that at some point landward of the maximum seaward position of the delta front, energy expended by waves reaching the subsiding shoreline was insufficient to erode the delta plain peat and mud deposits. Furthermore, the inherently high shear strength of the consolidated or semi-consolidated peat horizon would protect the underlying deltaic deposits from erosion. This general lack of coarse-grained clastic material associated with the transgressive flooding surfaces suggests that the transgressions were non-depositional displacements of the shorelines and sedimentation was, for the most part, restricted to periods of delta progradation (Asquith, 1974; Balsey, 1980).

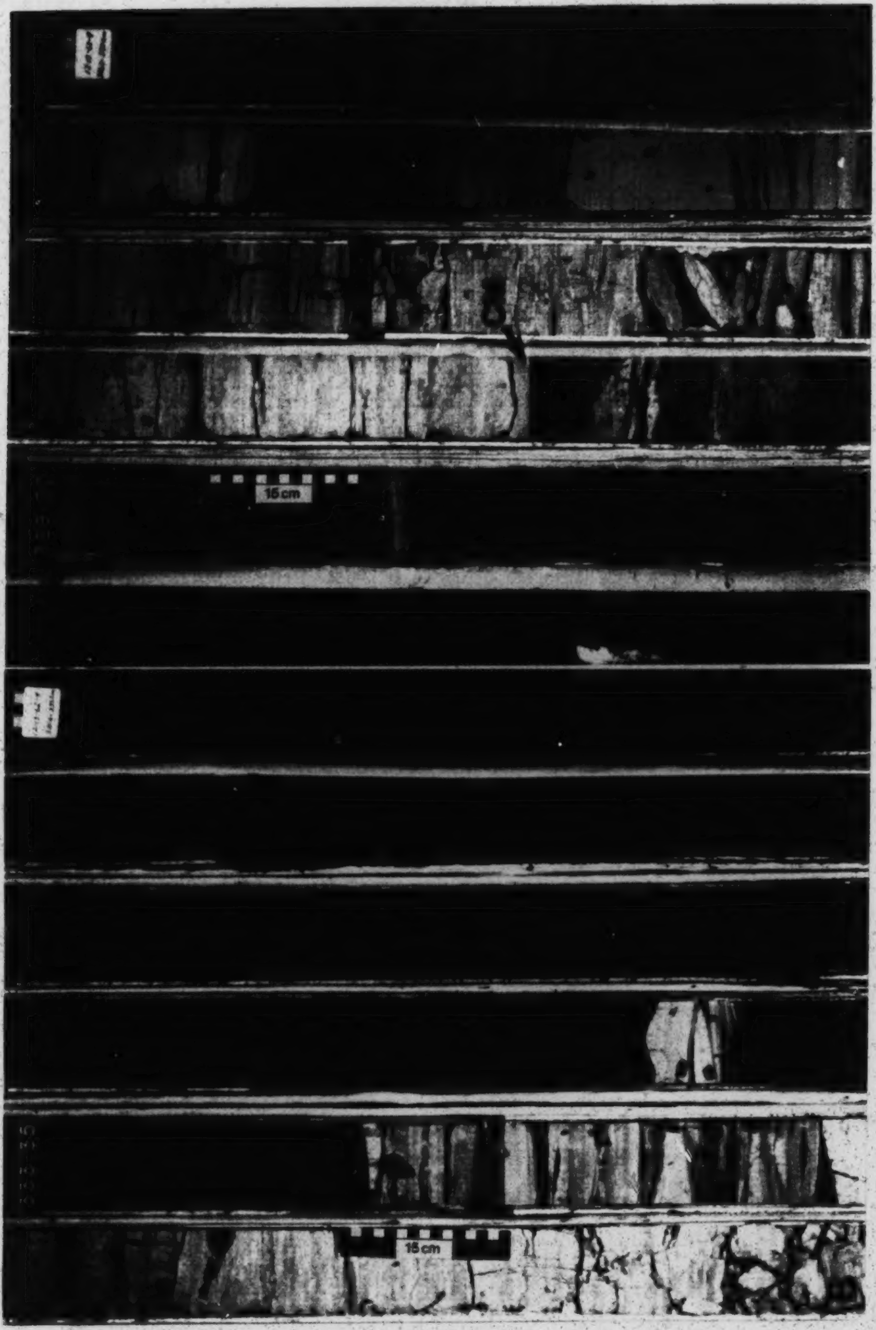
The GR_3 lithosome records the third cycle of deltaic sedimentation within the study area. Depositional conditions inferred to have existed during deposition of the GR_2 lithosome were reestablished during deposition of the GR_3 lithosome. The distribution of sandstone within the GR_3 lithosome displays a similar pattern as observed on modern fluvial-wave interaction deltas such as the Rhône delta. The Rhône delta front is characterized by a laterally extensive barrier-beach which is locally dissected by distributary channel sands (Oomkens, 1967). Typically the lower portion of the GR_3 lithosome comprises two delta front successions which record two cycles of progradation and intermittent delta abandonment and subsidence (Fig. 4.11; Fig. 4.12). Individual delta front successions, which reflect lobe progradation are separated by a thin unit of brackish water mudstones which was deposited during an episode of delta lobe switching and subsequent subsidence. Fluctuating brackish water salinity conditions are suggested by the presence of low diversity ichnofossil assemblages, abundant disseminated carbonaceous debris, incipient siderite cement and syneresis cracks.

The small-scale delta front successions which characterize the GR_2 and GR_3 lithosomes are interpreted to records the progradational of small "shoal-water" delta lobes similar to those described from the Recent Mississippi Delta (Fisk, 1955; Frazier, 1967; Elliot, 1986; Penland et al., 1988). Frazier (1967) identified four major delta complexes and fifteen discrete lobes formed by the Mississippi River in the past 6,000 years. These shoal-water deltas are characterized by sheet-like delta front sandstone bodies which extend over 800 km. Progradation of these deltas, due to the shallow water depth, is inferred to have been rapid, however, subsidence appears to have been slow and uniform across the entire delta lobe. The thickness of the delta front successions observed within the GR_2 and GR_3 lithosomes (average 6 to 8 m, maximum 12 m) is similar to the thickness values reported for the Recent Mississippi River shoal-water deltas which average 10 to 15 m (Frazier, 1967). The somewhat smaller values for the delta front successions observed within the GR_2 and GR_3 lithosomes is interpreted to reflect deposition in shallow water; less than that inferred for the Recent Mississippi River shoal-water deltas. The thickness of the prodeltaic mudstones (< 1.5 m) and the cumulative thickness of the delta front

Figure 4.11

GR_3 Lithosome

Typical coarsening-upwards delta front succession from the GR_3 lithosome. Interlaminated mudstones at the base of the sequence are overlain by a thin unit of interbedded mudstones and sandstones. The interbedded sandstones are overlain by a thick unit of large-scale cross-stratified sandstones. The predominance of large-scale cross-stratification is indicative of strong to moderate, persistent wave reworking. The delta front succession terminates with a thin delta plain deposit which comprises carbonaceous, rooted mudstones (CM). The carbonaceous mudstones are abruptly overlain by bioturbated, interlaminated mudstones of the basal GR_4 lithosome. The interlaminated mudstones grade upwards into interbedded sandstones and mudstones. Note the abundance of siderite cemented mudstone in the basal portion of the GR_4 lithosome. The photograph is from 12-13-62-4W4, 326-325 m. Scale bar gradations are in centimeters.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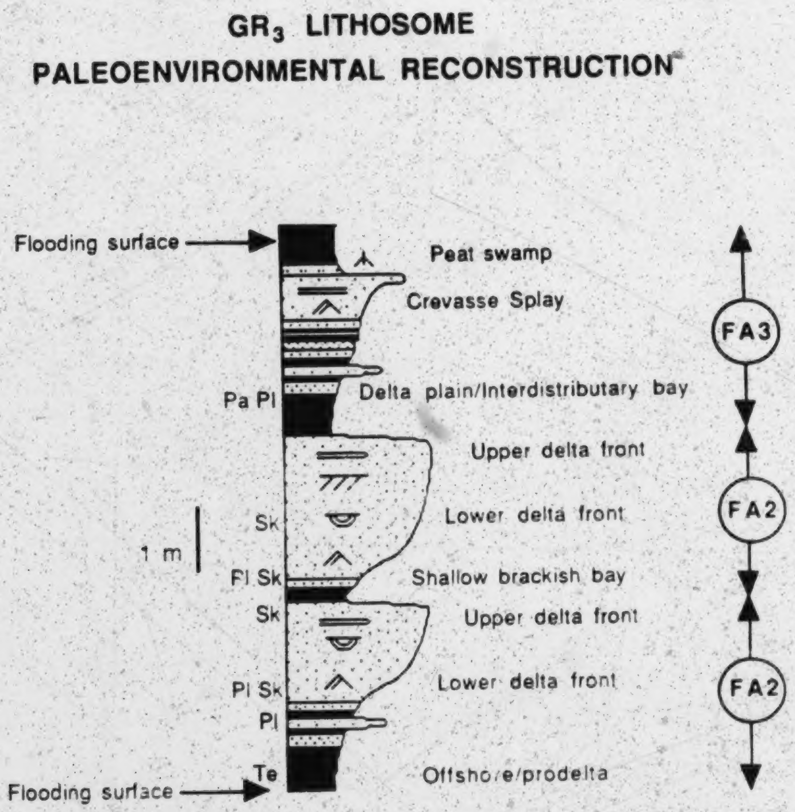


Fig. 4.12 Paleoenvironmental interpretation of the GR$_3$ lithosome. Typically, the GR$_3$ lithosome consists of two coarsening-upwards delta front successions which record two periods of intermittent delta progradation. The upper portion of the GR$_3$ lithosome is characterized by the development of delta plain deposits. Locally, distributary channels have incised into and replaced the delta front and delta plain deposits. Refer to the legend in the appendix for an explanation of the symbols and abbreviations utilized in this figure.

successions (average 6 to 8 m, maximum 12 m) suggests that water depth remained relatively shallow throughout deposition, perhaps locally less than 10 meters (*cf.* Klein, 1974). The low gradient of the depositional surface and the shallow water depth, inferred for the Grand Rapids Formation, effectively controlled the rate of progradation and subsidence in addition to the geometry and thickness of the delta front successions.

The upper portion of the GR_3 lithosome is characterized by the extensive development of delta plain deposits. Figure 4.13 is a schematic reconstruction of the depositional environment of the upper portion of the GR_3 lithosome, and illustrates the genetic relationship between the delta front, delta plain, and the distributary channel deposits. Small-scale fining- and coarsening-upwards successions (Facies Association 3) reflect the processes of overbank flooding, crevassing and channel avulsion and the progressive infilling of the shallow interdistributary bays. Coeval deposition of the bay-fill and distributary channel facies associations is suggested by a widespread rooted carbonaceous mudstone horizon which overlies both the bay-fill and distributary channel deposits. Furthermore, crevasse splay deposits, which form the upper portions of the bay-fill cycles, are well-developed in the vicinity of the distributary channels suggesting a genetic relationship between these two facies associations. Carbonaceous mudstones and thin coal laminae are common at many stratigraphic levels within the GR_3 lithosome reflecting the localized development of delta plain marsh and peat swamp subenvironments.

As observed within the GR_2 lithosome, distributary channels have incised into underlying delta front and delta plain deposits within the GR_3 lithosome. Channel incision is interpreted to have occurred in response to upstream switching of the channel course in response to progradation of the entire delta system. The stratigraphic relationship between the delta front, bay-fill and delta plain deposits suggests that this event post-dated delta plain sedimentation but pre-dated deposition of the carbonaceous mudstone or argillaceous coal horizon. This relationship between the channel-fill deposits and the overlying carbonaceous mudstone horizon suggests that avulsion or abandonment of the channel complex may have been concurrent with abandonment of the entire delta lobe (*cf* Elliot,

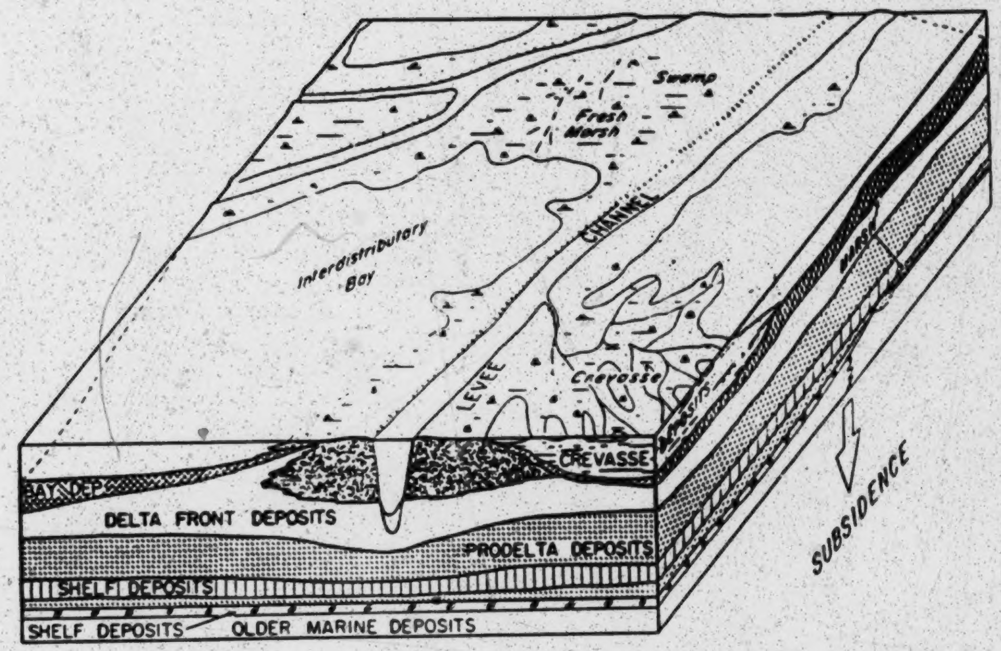


Figure 4.13 Schematic paleoenvironmental reconstruction of the upper GR_3 lithosome illustrating the genetic relationship between the delta plain, delta front and distributary channel-fill deposits (After Coleman, 1982).

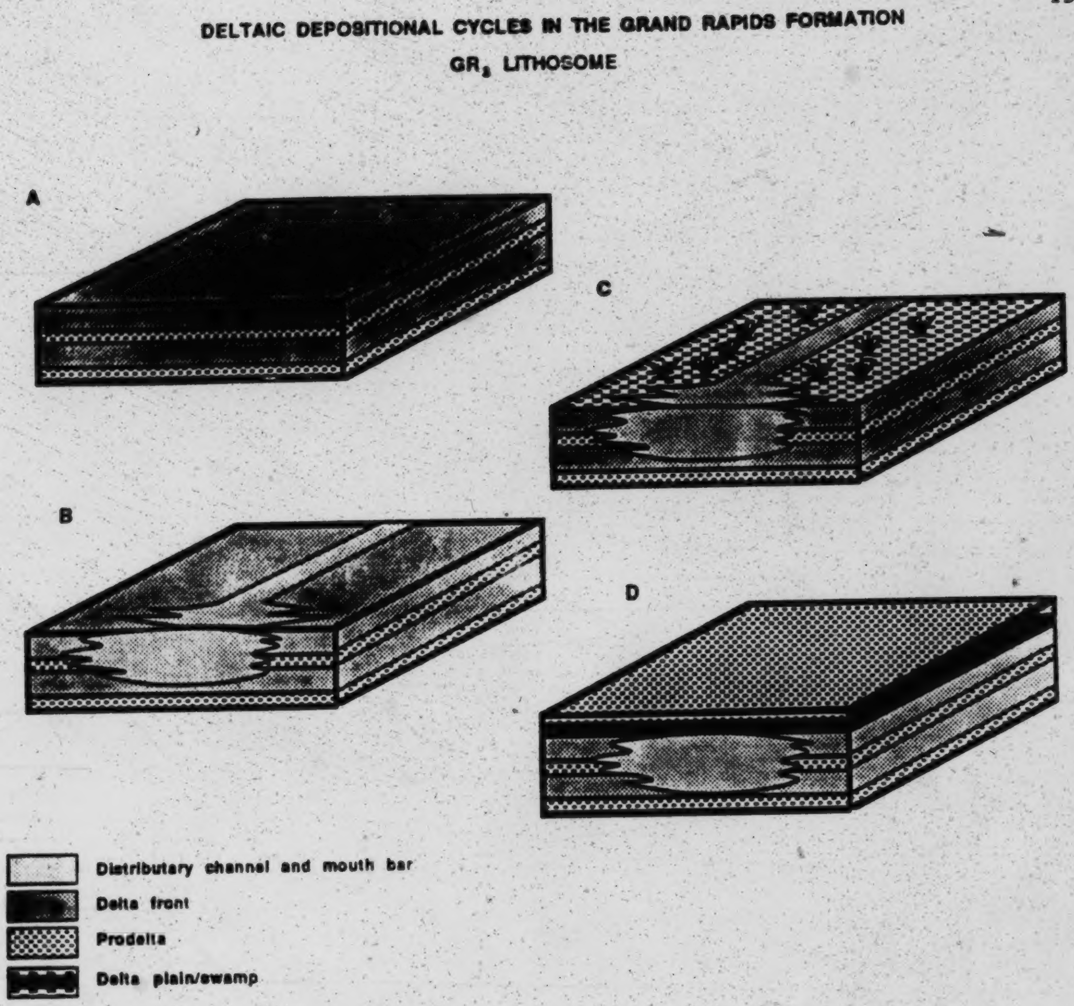

DELTAIC DEPOSITIONAL CYCLES IN THE GRAND RAPIDS FORMATION
GR_3 LITHOSOME
A
B
C
D
Distributary channel and mouth bar
Delta front
Prodelta
Delta plain/swamp

Figure 4.14 Schematic diagram illustrating the relationship between the distributary channel-fill deposits and the delta front and delta plain deposits.

A) Two periods of delta progradation resulting in the superposition of two delta front successions.

B) Incision of distributary channels into underlying delta front and coeval delta plain deposits.

C) Early stage of delta abandonment. Development of peat-forming swamps in the interdistributary areas and the aggradation of sediment within the distributary channels.

D) Late stage of delta abandonment. Increase in the rate of relative sea level rise resulting in the development of a peat horizon uniformly atop of the delta plain and channel-fill deposits. Continued sea level rise resulting in the flooding of the delta plain and the subsequent initiation of the next interval of regressive deltaic sedimentation.

1974; Fig. 4.14). The loss of the hydraulic effiency of the distributary channels resulted in an abrupt decrease in sediment supplied to the deltaic shorelines, and subsequently subsidence and abandonment of the entire delta lobe.

Brown (1965) and Vigrass (1977) suggest that these large-scale channel-fill complexes developed in the upper portions of the Sparky Formation (correlative to the GR_3 lithosome) define a regional intra-Mannville Group unconformity. As such this surface represents a type-1 unconformity of Vail *et al.* (1977) and Van Wagoner *et al.* (1988). Evidence suggestive of episodes of rapid sea level fall, necessary to develop a regional unconformity, such as the presence of paleosols or root zones at or near the base of the channel-fill successions (*cf.* Weimer, 1984), have not been observed within the study area.

A laterally continuous carbonaceous mudstone horizon culminates the GR_3 lithosome and extends uniformly across the channel-fill and bay-fill successions. This carbonaceous mudstone horizon terminates the progradational phase of deltaic sedimentation, and records the initial portion of the abandonment phase of the deltaic sedimentation cycle and the establishment of extensive peat-forming swamps following lobe abandonment (Elliot, 1976). The uniform distribution of this horizon, overlying both the bay-fill and channel-fill deposits, indicates that abandonment of the delta lobe was a consequence of upstream distributary channel switching and abandonment. An increase in the rate of subsidence resulted in the compaction of delta plain deposits, eventual submergence of the delta plain platform and the establishment of shallow, brackish water bay conditions within the study area.

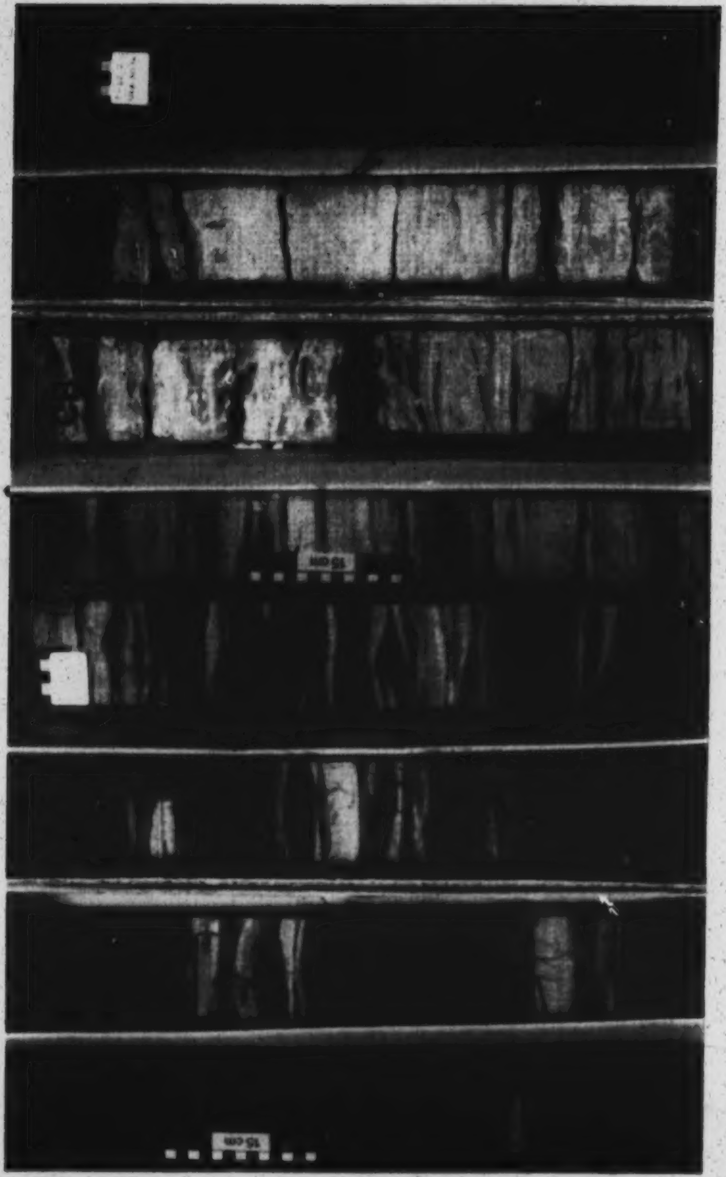
This carbonaceous mudstone horizon may be correlative to the Sparky Coal, a laterally persistent horizon recognized within the Lloydminster area, which is commonly utilized to define the top of the Sparky Formation (Smith, 1984; Putnam, 1988). While the mudstone horizon recognized within the study area may not be directly correlatable with the Sparky coal, it may suggest that the termination of regressive sedimentation may have been a regional, but not necessarily a contemporaneous event.

The GR_4 lithosome records a significant change in the nature of the depositional system within the vicinity of the study area. Wave-influenced or wave-dominated deltaic sedimentation, which characterizes the GR_1, GR_2, and GR_3 lithosomes, was not re-established during deposition of the GR_4 lithosome. Instead, the GR_4 lithosome and the remainder of the Grand Rapids Formation (GR_5 and GR_6 lithosomes) are characterized by fluvial-dominated delta plain sedimentation. This change from wave-dominated sedimentation to fluvial-dominated deposition is interpreted to reflect a basinward shift in depositional environments. Two processes or mechanisms may have operated independently or in combination to produce this effect. A decrease in the magnitude of relative sea level rise following deposition of the GR_3 may have effectively decreased the volume of the depositional basin. Such a change in accommodation space would result in a basinward shift of depositional environments. The second possible mechanism is related to regional tectonic events. The lower and middle Mannville Subgroups (Vigrass, 1977) strata (Dina, Cummings, Lloydminster, Rex, General Petroleums and Sparky formations) were derived from the Pre-Cambrian shield and distributed as deltaic sediments within the Lower Cretaceous Clearwater sea (Mellon and Wall, 1963; Williams, 1963). The strata of the upper Mannville Group were derived from the emerging Cordillera (Williams, 1963; Mellon, 1967; Carrigy, 1977; Miall, 1978; Putnam and Oliver, 1980; Putnam, 1982) and to a lesser degree the Pre-Cambrian shield (Orr et al., 1977; Putnam and Oliver, 1980). Uplift and erosion of the emerging Cordillera would have increased the volume of terrigenous clastic sediments supplied to the depositional basin. This increase in sediment influx resulted in a basinward shift in the locus of active deltaic sedimentation and the accumulation of extensive delta plain deposits within the vicinity of the study area.

As previously mentioned the GR_4 is characterized by extensive fluvial-dominated delta plain sedimentation (Fig. 4.15). Within the GR_4 lithosome two major depositional subenvironments have been recognized: distributary channels and interdistributary bays. Unlike the previously discussed lithosomes, the preserved sedimentary record is dominated by channel deposition. There appears to be at least two stratigraphic levels of channel deposition within the GR_4 lithosome. The first episode of channel deposition is

Figure 4.15
GR_4 Lithosome

A representative example of a small-scale distributary channel-fill succession from the GR_4 lithosome which culminates with a thin argillaceous coal bed (CB). This coal horizon is abruptly overlain by bioturbated mudstones of the basal GR_5 lithosome. As such, the top of this horizon represents the flooding surface which separates the GR_4 lithosome from the GR_5 lithosome. The photograph is from 7-1-62-2W4, 322.8-328.6m. Scale bar gradations are in centimeters.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characterized by abundant small (6 to 10 m) distributary channel-fill successions of limited lateral extent (Fig. 4.16). These small-scale channel-fill successions laterally interfinger with bay-fill successions (Facies Association 3). Typically, the bay-fill successions are comprised of carbonaceous and sideritic mudstone and only exhibit a slight coarsening-upwards grain size trend. Occasionally, very fine- to fine-grained sandstones are preserved in the upper portions of the bay-fill successions. These coarser-grained beds are interpreted to reflect rare, high energy events in which flood waters breached the channel levees and deposited coarse sediments in the interdistributary bay. This distinct absence of sandstone within the majority of the bay-fill successions suggests that coarse clastic deposition was primarily confined to the distributary channel complexes. The second episode of channel deposition within the study area is represented by a large-scale (20-35 m thick, 0.5-2.5 km wide) north or north northeast trending distributary channel complex which erosively overlies and incises into the channel-fill and bay -fill deposits of the first cycle of deposition within the GR_4 lithosome. In contrast to the channel-fill deposits of the first cycle, there does not appear to be any evidence of significant overbank deposition. Since the distributary channels have incised into underlying channel-fill and bay-fill deposits, following incision, and in response to rising relative sea level, aggradation became the predominant process and sedimentation was confined to the channels. Abundant intraclast strewn surfaces within the channel-fill successions and the vertical repetition of facies suggest that the channels have undergone a complex history of repeated erosion, accretion and aggradation.

A diminished, yet distinct, marine influence is suggested by the well-developed brackish water ichnofaunal assemblages and abundant sedimentary structures, suggestive of tidal processes, found within the channel-fill deposits, indicative of a marginal marine setting. The preserved physical and biogenic sedimentary structures and the overall geometry of the channel-fill complexes is similar to that observed in modern estuarine and tide-influenced deltaic settings. Since estuarine and tidally-influenced deltaic distributaries are depositionally similar, discrimination is primarily related to relative sea level. Putnam (1980, 1982, 1983) and Putnam and Oliver (1980) suggested that the majority of the upper

GR$_4$ LITHOSOME PALEOENVIRONMENTAL RECONSTRUCTION

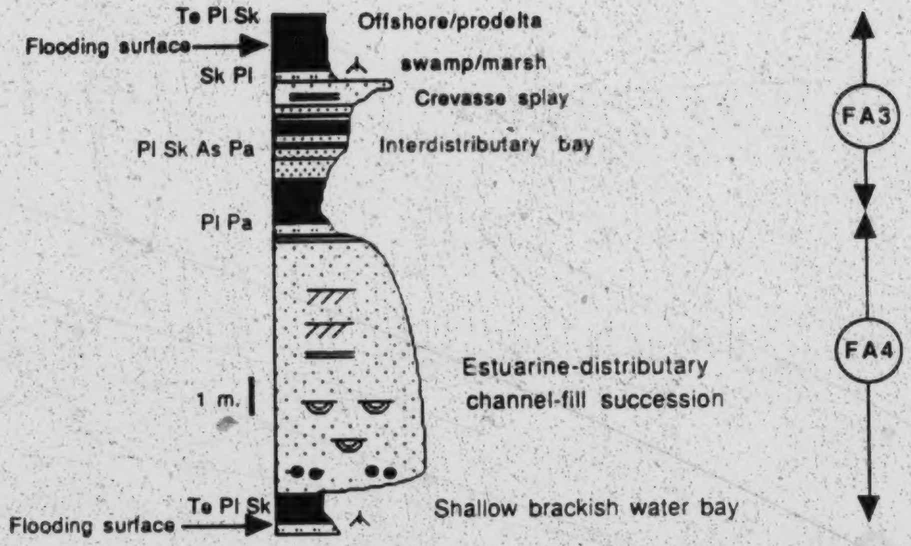


Fig. 4.16 Paleoenvironmental reconstruction of the GR$_4$ lithosome. Typically, the GR$_4$ lithosome consists of a basal distributary/ estuary channel-fill succession which may be overlain by bay-fill deposits. Commonly, the entire GR$_4$ lithosome consists of a single distributary channel-fill succession. Refer to the legend in the appendix for an explanation of the symbols and abbreviations utilized in this figure.

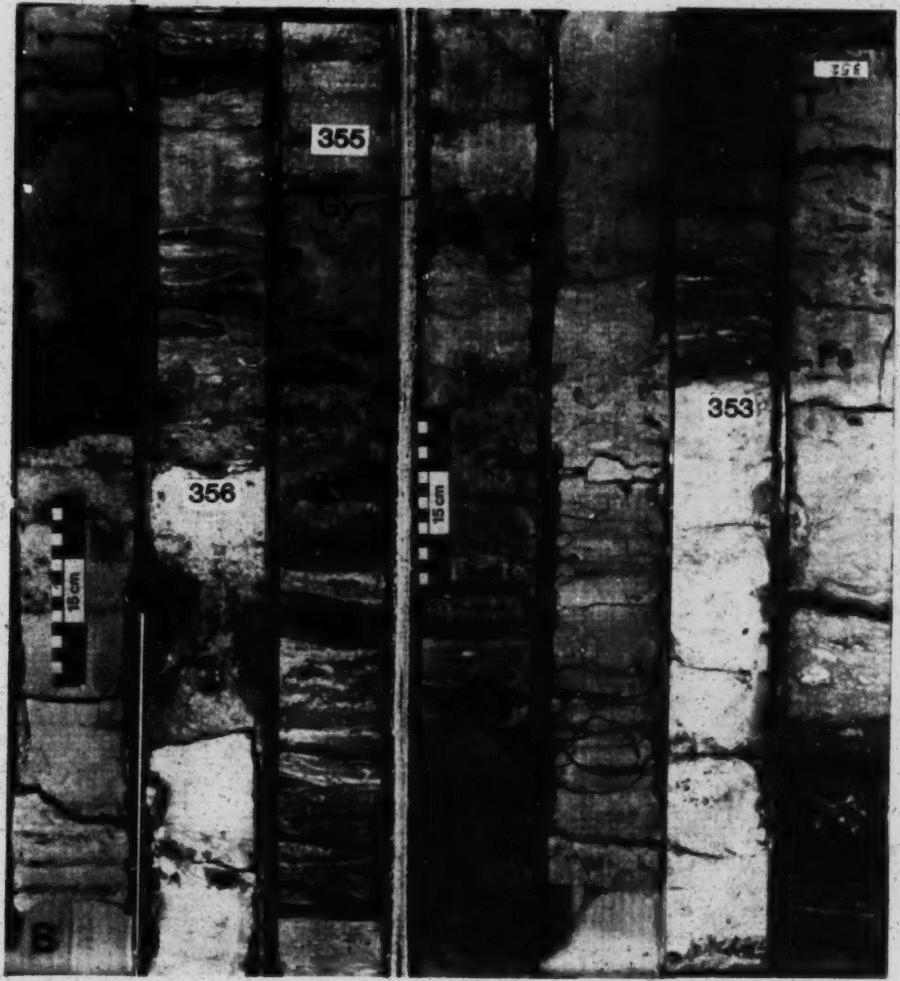
Mannville Group (GR_4, GR_5 and GR_6 lithosomes in this study) consists of anastomosing-fluvial deposits. However, within the study area the recognition of physical and biogenic sedimentary structures indicative of marine processes precludes an anastomosing interpretation, and favours a tidally-influenced deltaic setting.

The origin of the large-scale channel-fill successions is to be related to autocyclic processes inherent within a deltaic depositional system; specifically channel switching and delta lobe abandonment. Due to the development of an unstable hydraulic gradient, the distributary channel complex switched its course upstream to develop a more stable gradient; subsequently, incising into underlying bay-fill deposits. As previously mentioned, the uniform distribution of a carbonaceous mudstone horizon overlying both the bay-fill and channel-fill successions suggests that this incision event immediately preceded the abandonment of the entire delta complex. Slowly rising base level would promote the aggradation and accumulation of thick channel-fill successions within a delta plain setting. During the later stages of channel-fill deposition, peat-forming swamps and marshes developed in the interdistributary areas. As the rate of relative sea level rise increased, channel-filled deposition ceased and both the channel-fill and bay-fill deposits were overlain by extensive, carbonaceous swamp and marsh deposits. The paleoenvironment interpretations proposed for the GR_4 lithosome are very similar to the interpretation proposed for the correlativeWaseca Formation within the Lloydminster area by MacEachern (1984, 1989) and Van Hulten (1984).

The GR_5 lithosome records the local reestablishment of fluvial-dominated sedimentation within the study area. A relative sea level fall or an increase in sediment influx into the depositional basin following transgression of the GR_4 delta plain initiated another interval of regressive bay-fill sedimentation (Fig. 4.17). Typically the GR_5 lithosome is characterized by two small-scale (6 to 10 m) coarsening-upwards successions which record the progressive infilling of a shallow, brackish water bay (Fig. 4.18). Small-scale (4 to 8 m) distributary channel-fill deposits which appear to be coeval with the bay-fill deposits are locally encountered throughout the study area. Well spacing and the size of

Figure 4.17
GR_5 Lithosome

A representative example of a coarsening-upwards bay-fill succession from the GR_5 lithosome which records the progressive infilling of shallow interdistributary bays. The basal portion of the succession consists of interlaminated mudstones with abundant syneresis cracks and low diversity ichnofossil assemblages dominated by *Planolites*. Upwards, the interlaminated mudstones are replaced by thoroughly bioturbated interbedded mudstones and sandstones. This interbedded unit grades upwards into thoroughly bioturbated small-scale cross-stratified and planar-laminated sandstones. These sandstones are characterized by high density, low diversity ichnofossil assemblages dominated by *Gyrolithes* (Gy). The bay-fill succession terminates with a highly disrupted, bioturbated carbonaceous mudstone unit. Carbonaceous debris, coal clasts and rootlets are common in the upper portion of this unit. The carbonaceous mudstones of the uppermost GR_5 lithosome are abruptly overlain by bioturbated mudstone of the basal GR_6 lithosome. FS marks the flooding surface which separates the GR_5 lithosome and the GR_6 lithosome. The photograph is from 10-15-61-1W4, 352-357 m. Scale bar gradations are in centimeters.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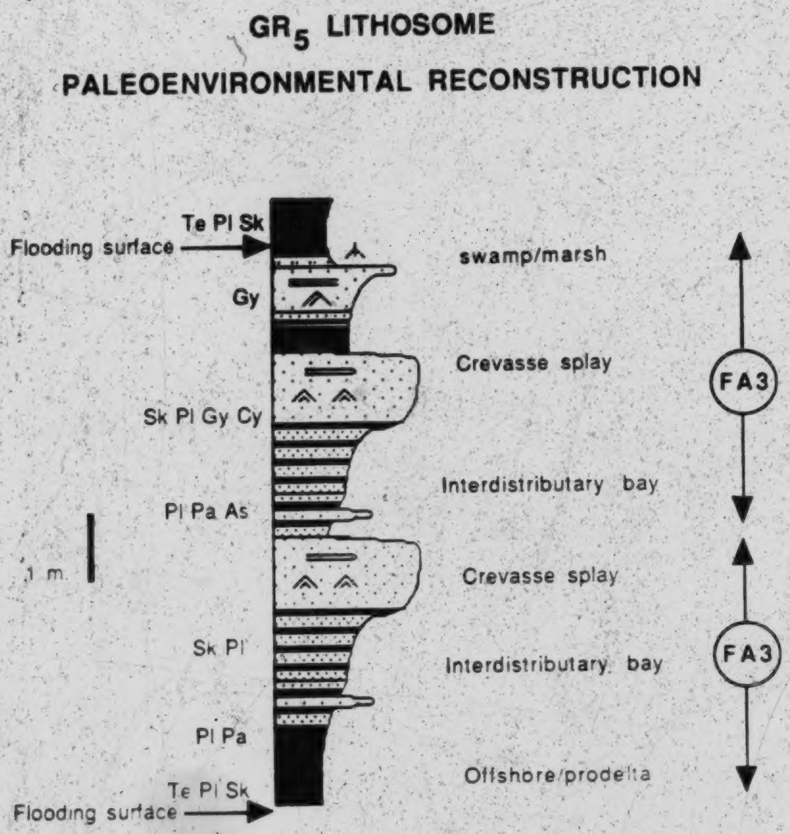
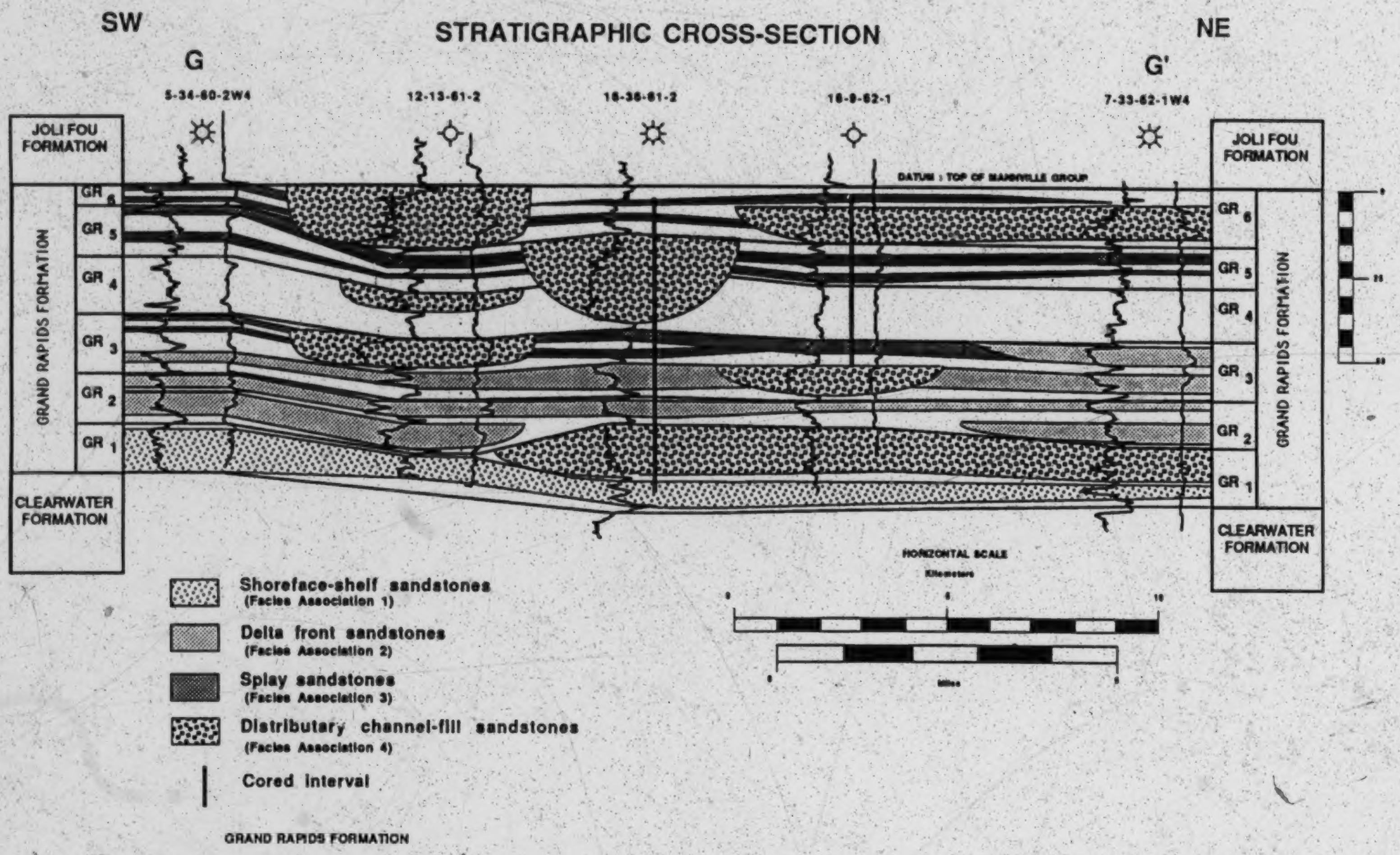


Fig. 4.18 Paleoenvironmental reconstruction of the GR_5 lithosome. Typically, the GR_5 lithosome consists of two vertically, stacked coarsening-upwards bay-fill successions which are, in the central portion of the study area, disected by a narrow distributary channel-fill complex. Refer to the legend in the appendix for an explanation of the symbols and abbreviations utilized in this figure.

these channel-fills hinders the recognition of any significant trends. Crevasse splay sandstones, which form the upper portions of the bay-fill successions, are well-developed in close proximity to the distributary channel-fill deposits suggesting a genetic relationship between these two facies associations. Within the central portion of the study area, a predominantly east-west trending distributary channel complex is deeply incised into the coarsening-upwards bay-fill successions. Locally, these distributary channel deposits may attain thicknesses in excess of 20 meters. In the 16-36-61-2W4 wellbore, a large-scale channel-fill succession is incised into and has removed the majority of the underlying GR_4 lithosome strata (Figs. 4.19 and 4.20). Immediately adjacent to this channel-fill complex, a number of bay-fill cycles are vertically stacked, indicating that this are was prone to repeated crevassing.

A persistent rooted, carbonaceous mudstone horizon overlies both the bay-fill and distributary channel fill successions. This carbonaceous mudstone horizon reflects the initial deposits of the abandonment phase of deltaic sedimentation and indicates that abandonment of the delta complex was accompanied by widespread swamp/marsh development. Incision of the distributary channel complex into the underlying bay-fill deposits is interpreted to have occurred in response to upstream avulsion and subsequent channel switching. The stratigraphic relationships between the bay-fill deposits, distributary channel-fill deposits and the carbonaceous mudstones suggests that abandonment of the distributary channel complex was concurrent with abandonment and transgression of the entire delta complex.

The GR_6 lithosome records the final deltaic depositional cycle within the study area. The pattern of sedimentation displayed within the GR_6 lithosome is very similar to that observed within the GR_5 and GR_4 lithosomes in that the GR_6 lithosome is characterized by cyclical bay-fill deposits and small-scale distributary channel-fill successions (Figs. 4.21 and 4.22). Abundant carbonaceous debris, coal laminae and a restricted brackish water ichnofaunal assemblages within the distributary channel-fill and bay-fill successions of the GR_6 are suggestive of an increased continental influence and deposition in an upper delta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STRATIGRAPHIC CROSS-SECTION
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G
G'
5-34-60-2W4
12-13-61-2
16-36-61-2
16-9-62-1
7-33-62-1W4
JOLI FOU FORMATION
GRAND RAPIDS FORMATION
CLEARWATER FORMATION
GR 6
GR 5
GR 4
GR 3
GR 2
GR 1
DATUM : TOP OF MANNVILLE GROUP
HORIZONTAL SCALE
Kilometers
0
5
10
0
Miles
5
Shoreface-shelf sandstones (Facies Association 1)
Delta front sandstones (Facies Association 2)
Splay sandstones (Facies Association 3)
Distributary channel-fill sandstones (Facies Association 4)
Cored interval
GRAND RAPIDS FORMATION

Figure 4.19 Stratigraphic cross-section G-G' illustrating the distribution of sandstone bodies in the Grand Rapids Formation.

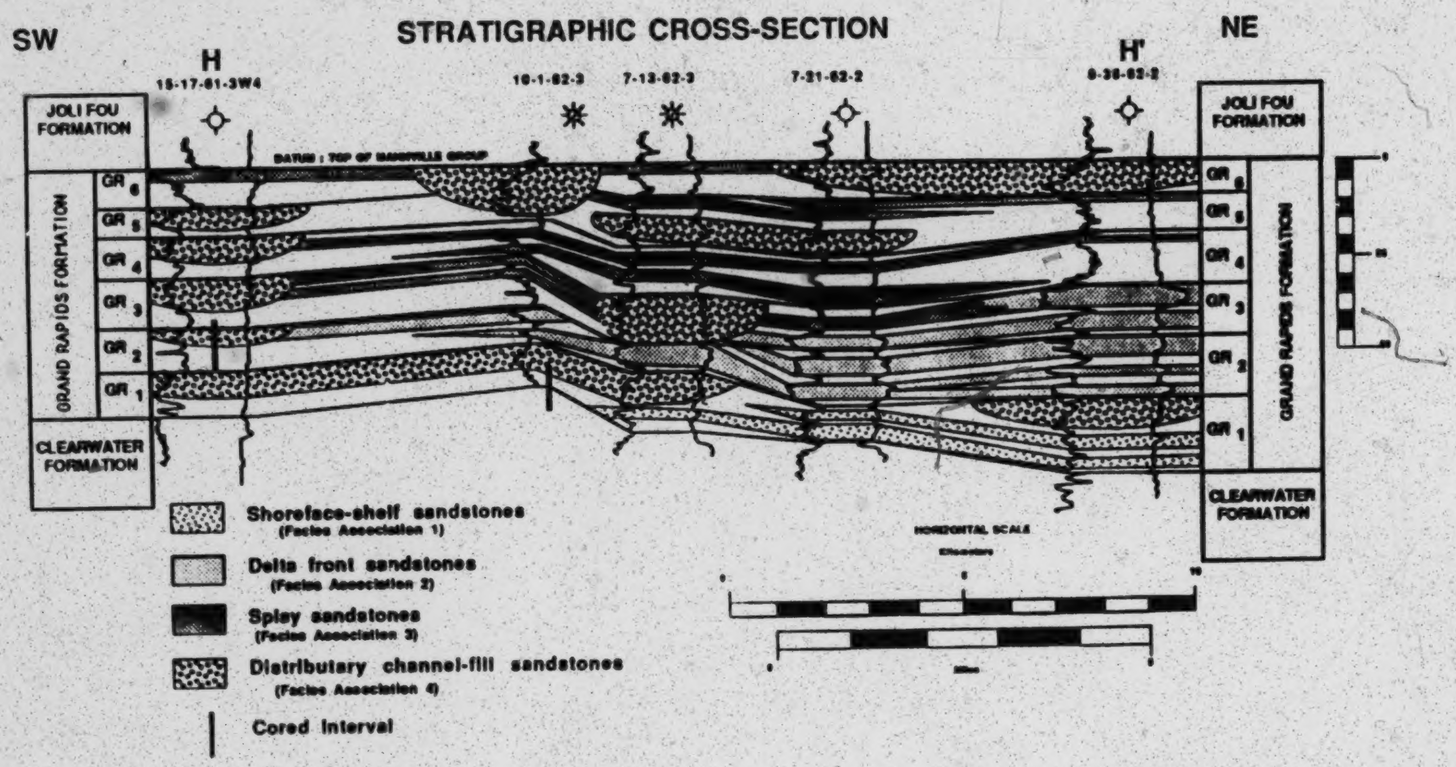

STRATIGRAPHIC CROSS-SECTION
SW
NE
H
15-17-61-3W4
10-1-62-3
7-13-62-3
7-21-62-2
H'
8-36-62-2
DATUM : TOP OF MANNVILLE GROUP
JOLI FOU FORMATION
GRAND RAPIDS FORMATION
GR 6
GR 5
GR 4
GR 3
GR 2
GR 1
CLEARWATER FORMATION
Shoreface-shelf sandstones (Facies Association 1)
Delta front sandstones (Facies Association 2)
Splay sandstones (Facies Association 3)
Distributary channel-fill sandstones (Facies Association 4)
Cored Interval
HORIZONTAL SCALE
Kilometers
0
5
10
0
5
Miles

Figure 4.20 Stratigraphic cross-section H-H' illustrating the distribution of sandstone bodies in the Grand Rapids Formation.

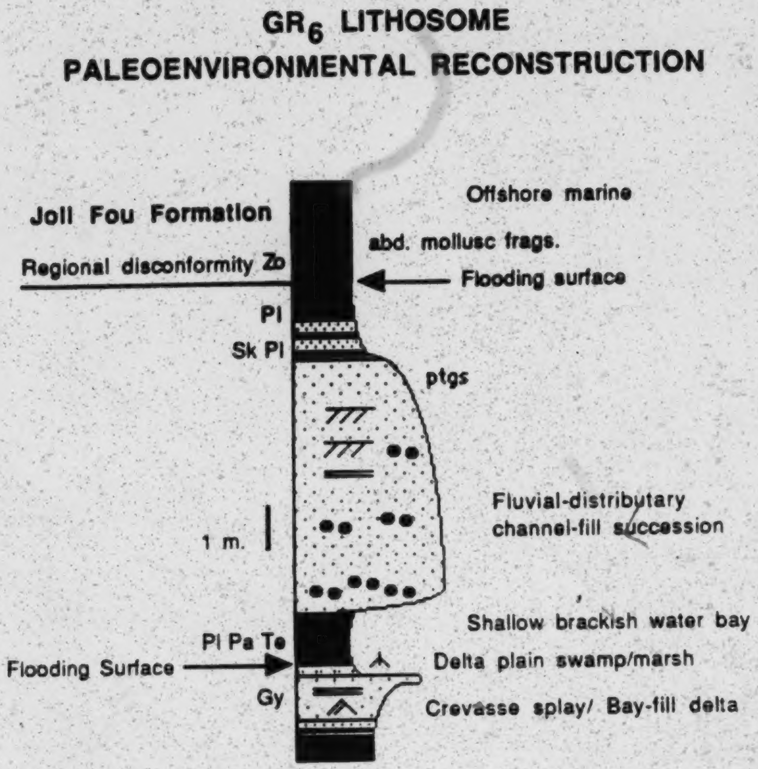

GR6 LITHOSOME
PALEOENVIRONMENTAL RECONSTRUCTION
Joli Fou Formation
Regional disconformity Zo
Offshore marine
abd. mollusc frags.
Flooding surface
Pl
Sk Pl
ptgs
1 m.
Fluvial-distributary channel-fill succession
Pl Pa Te
Shallow brackish water bay
Flooding Surface
Delta plain swamp/marsh
Gy
Crevasse splay/ Bay-fill delta

Fig. 4.20 Paleoenvironmental reconstruction of the GR_6 lithosome. The GR_6 lithosome records the final deltaic depositional cycle within the study area. Within the study area the GR_6 lithosome is dominated by fluvial-distributary channel deposition.

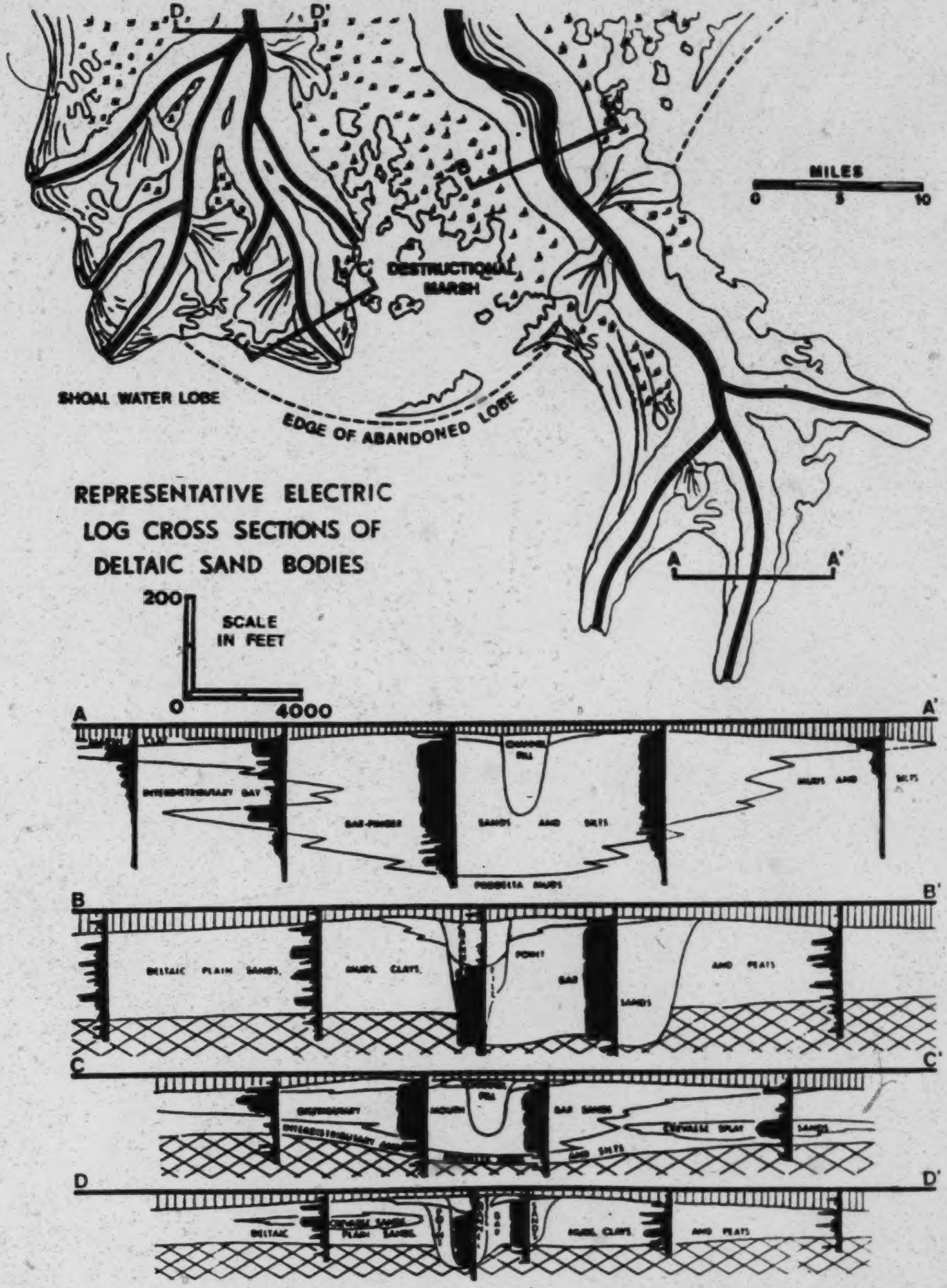


Figure 4.22 Cross-sections and schematic map illustrating the distribution of deltaic sandstone bodies in the GR_6 lithosome (After Galloway, 1975).

plain or alluvial plain setting.

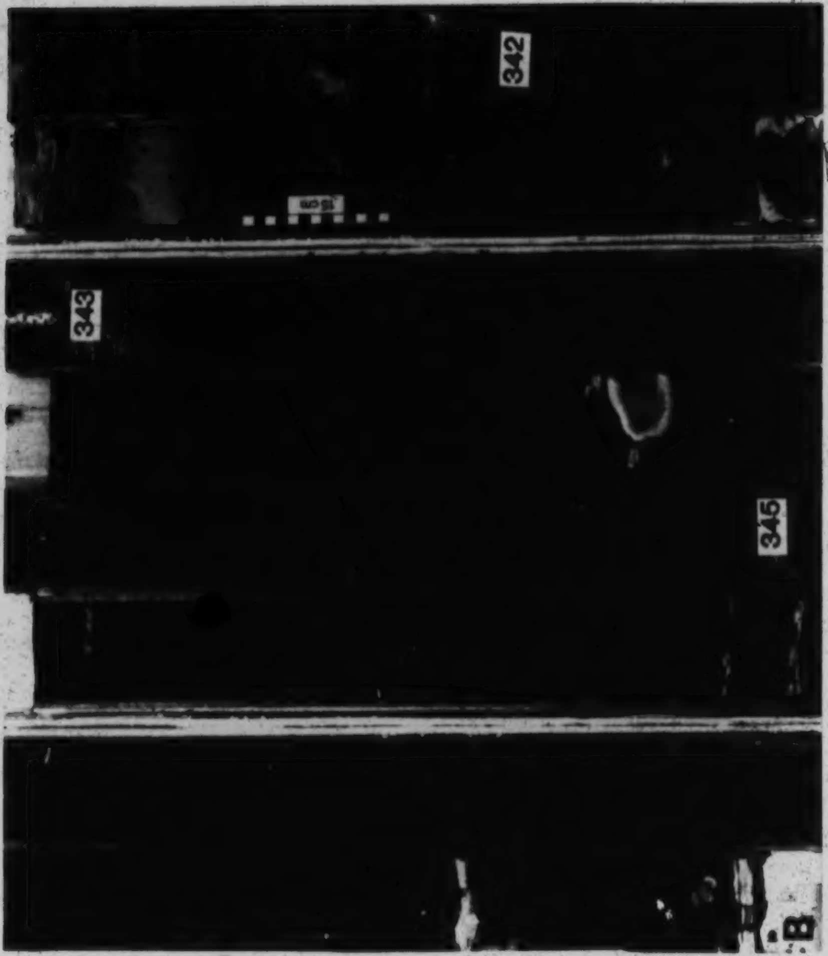
As observed within other lithosomes, late stage distributary channel-fill successions are found within the GR_6 lithosome. In the GR_6 lithosome these channel-fill successions are exceptionally thick (25 to 40 m), and in the eastern portions of the study area have incised and replaced strata of the underlying GR_5 lithosome, and locally the GR_4 lithosome. Figure 4.23 is a representative cored sequence of a distributary channel-fill succession from the upper portion of the GR_6 lithosome. The channel-fill successions observed within the GR_6 lithosome differ slightly from those observed in other lithosomes. In the GR_6 lithosome, the channel-fill successions are dominated by either high-angle, large-scale cross-stratified sandstones or massive sandstones with abundant mudstone intraclasts. Furthermore, unlike the channel-fill succession encountered in other lithosomes, physical sedimentary structures such as mudstone partings, drapes and tidal bundles which are interpreted to be indicative of tidal influence, are typically not observed. Also biogenic sedimentary structures are much less prevalent in the GR_6 lithosome than in any other lithosome. A weak, yet distinct marine influence is suggested by the occurrence of a restricted, very low diversity, low density ichnofossil assemblages. As such, deposition of the GR_6 lithosome is interpreted to have occurred near or landward of the maximum influence of tidal currents and other marine processes. Therefore, in terms of the entire Grand Rapids Formation depositional sequence, the GR_6 lithosome is interpreted to represent the development of maximum regressive conditions.

In contrast to the other lithosomes, the carbonaceous mudstone horizon which typically terminates the lithosome, is not developed in the GR_6 lithosome. Instead, the GR_6 lithosome culminates with a thin (0.3 to 1.3 m) micaceous, thoroughly bioturbated, locally calcite-cemented sandstone. This horizon is interpreted to represent a coarse-grained transgressive deposit and suggests that abandonment of the GR_6 lithosome delta complex, and termination of Grand Rapids Formation deposition, was accompanied by widespread erosion. Locally, erosion associated with this event is indicated by a lag of calcite- and siderite-cemented clasts overlying the GR_6 lithosome transgressive flooding surface. This

Figure 4.23

GR_6 Lithosome

Core sequence from the upper portion of a distributary channel-fill succession from the GR_6 lithosome. Typically, the channel-fill successions encountered within the GR_6 lithosome are dominated by high angle, large-scale cross-stratified sandstones or massive sandstones with abundant mudstone intraclasts. Physical and biogenic sedimentary structures indicative of marine processes are typically not observed within the channel-fill succession in the GR_6 lithosome. The arrow points to the Grand Rapids Formation - Joli Fou Formation contact. The photograph is from 10-15-61-1W4, 341.5-347 m. Scale bar gradations are in centimeters.


342
10 cm
343
345
B

surface of erosion defines a regional unconformity which defines the top of the Mannville Group. Continued sea level rise resulted in the deposition of the overlying Joli Fou Formation shales which record a basinwide transgressive event during Late Albian time (Stott, 1984).

4.3 Sedimentological Model and Summary

The Grand Rapids Formation was deposited during a third-order eustatic sea level rise which spanned the Aptian to early Late Albian/ Early Cenomanian (Vail, 1977; Kauffman, 1977; Hancock and Kauffman, 1979; Haq et al., 1987; Possmatier et al., 1988) Despite this period of sea level rise, the Grand Rapids Formation is dominated by multiple, stacked regressive deltaic sandstones. The most characteristic feature of the Grand Rapids Formation is the vertical repetition of facies and depositional environments (Fig. 4.24). Many authors have previously noted this cyclic pattern of sedimentation within the Mannville Group, particularly within the Grand Rapids Formation equivalents of the Lloydminster area. In the Lloydminster area most of the Mannville Group is comprised of stacked coarsening-upwards successions of mudstones and sandstones which locally are overlain by coals or carbonaceous mudstones. Typically the origin of these cyclic deposits has been attributed to deposition within a progradational, wave-dominated shoreline setting (Orr et al., 1977; Vigrass, 1977; Smith, 1984; Van Hulten and Smith, 1984; Wilson, 1984). This pattern of cyclical transgressive-regressive sedimentation is not unique to the Mannville Group but predominates much of the rock record, particularly the Cretaceous deposits of the Western Interior (Kauffman, 1977; Weimer, 1984; Cross, 1988).

Each of the six lithosomes which subdivide the Grand Rapids Formation is interpreted to reflect an interval of deltaic sedimentation. Each lithosome is characterized by a predictable vertical succession of facies which reflect a particular interval of sedimentation. A typical deltaic depositional cycle begins with a regressive phase which records delta platform establishment followed by distributary mouth bar and delta front progradation. Each progradational phase was terminated by a destructional phase of

CYCLIC SEDIMENTATION WITHIN THE GRAND RAPIDS FORMATION

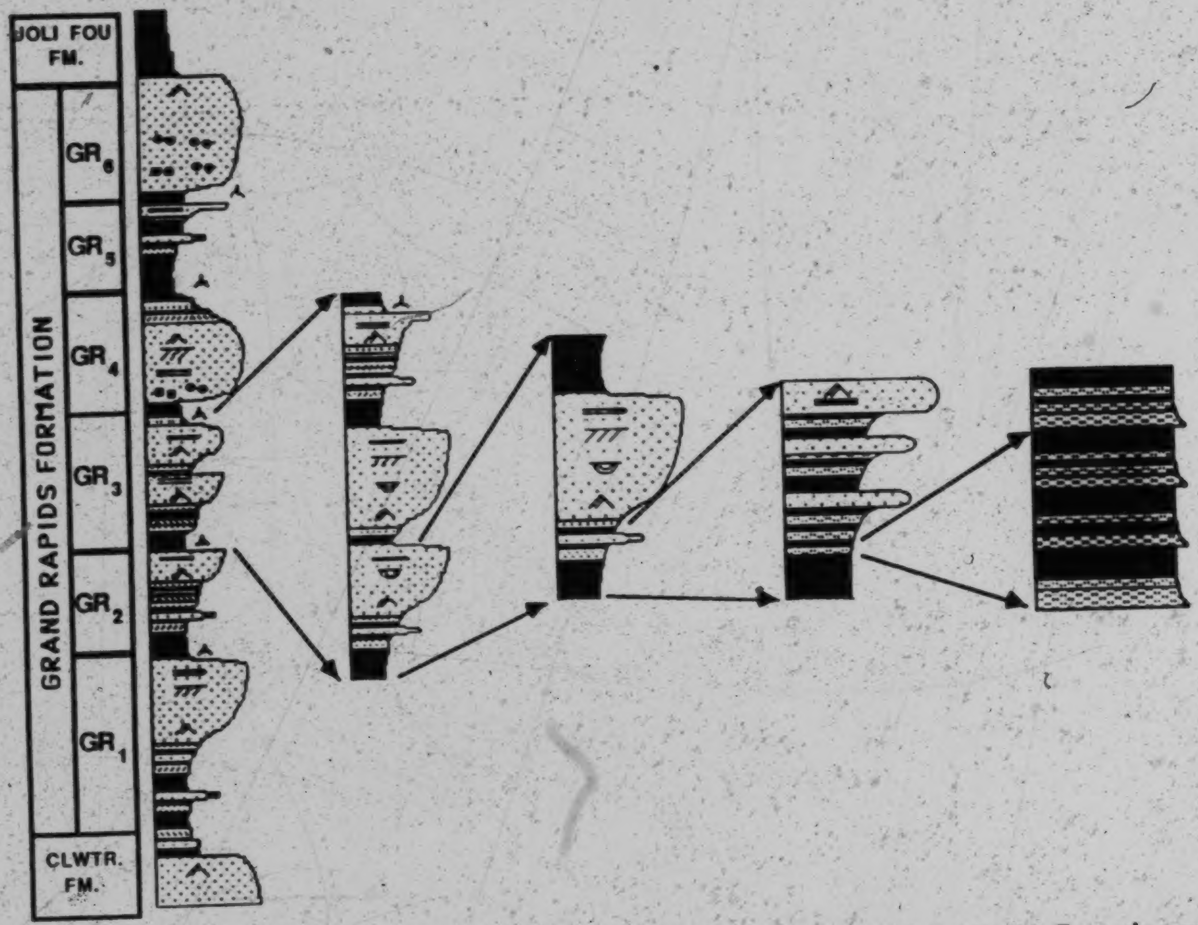


Figure 4.24 Several scales of cyclic sedimentation are evident within the Grand Rapids Formation, ranging from the scale of the lithosomes (15-40 m) to individual cyclic interlaminated mudstone beds (5-25mm).

subsidence and flooding. Each destructional phase is related to upstream avulsion, channel switching and abandonment of the distributary complex which downstream results in the formation of a new delta lobe and abandonment of the precursor lobe. Delta lobe abandonment was accompanied by widespread marsh development. Peat formation and delta plain accretion continued until subsidence exceeded the rate of sedimentation. At this point the delta plain was submerged, deltaic sedimentation was arrested and subsidence became the predominant process. This type of delta lobe switching, combined with continuous subsidence rates, produces stacked regressive sequences that occur at high frequencies. In the Recent Mississippi Delta a complete shoal-water delta lobe construction and abandonment cycle is estimated to require 3,200 to 5,700 years (Coleman, 1988).

The six lithosomes, each of which displays a progradational-transgressive pattern, are arranged in an overall progradation stacking pattern reflecting the continual basinward shift in the locus of active shoreline sedimentation throughout the deposition of the Grand Rapids Formation (Fig. 4.25). The lowermost GR_1 lithosome is characterized by relatively high energy wave-dominated deltaic sedimentation. Stratigraphically upwards, the evidence of strong wave influence progressively decreases in the GR_2 and GR_3 lithosomes. Concomitant with the decrease in overall wave energy, fluvial influence increases and salinity decreases. The GR_2 and GR_3 lithosomes record the intermittent progradation and abandonment of a number of shoal-water delta lobes. The overlying GR_4, GR_5 and GR_6 lithosomes record fluvial-dominated delta plain sedimentation. Evidence of wave and tidal processes becomes increasingly less noticeable and the ichnological signature of brackish water conditions becomes increasingly prevalent upwards with the GR_4, GR_5 and GR_6 lithosomes. The GR_4 lithosome is characterized by tide-dominated distributary channel-fill deposition. The GR_5 is characterized by bay-fill deposition. The preserved physical and biogenic sedimentary structures reflect deposition within low salinity brackish, tide- and wave-influenced interdistributary bays. The overlying GR_6 lithosome

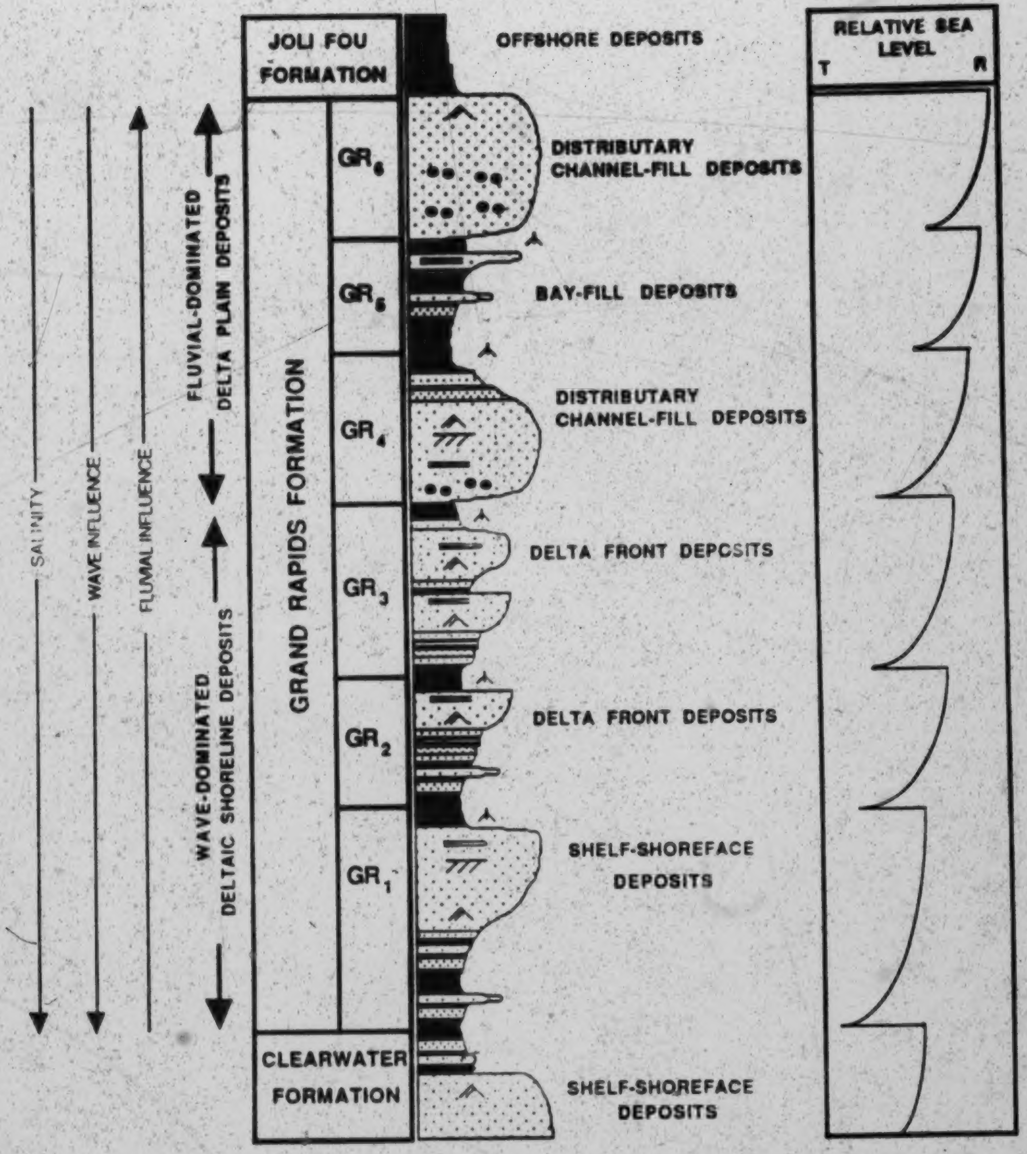


Figure 4.25 Paleoenvironmental summary diagram of the Grand Rapids Formation. The arrows indicate the direction of increasing influence. The term relative sea level refers to the combined of changes in the rate of sea level rise or fall, changes in the rate of subsidence or sediment influx.

records evidence of fluvial-dominated delta plain deposition. Sedimentologic evidence indicative of tide- and wave-related related processes is not readily apparent. As such, the GR_6 lithosome represents the establishment of maximum regressive conditions during deposition of the Grand Rapids Formation.

The application of an autocyclic delta model to the Grand Rapids Formation to explain the lateral and vertical facies relationships and cyclical pattern of sedimentation makes it unnecessary to invoke periodic pulses of basinal subsidence, cyclical eustatic sea level fluctuations or cyclical fluctuations in sediment supply. Rather the proposed model of deltaic sedimentation is self-perpetuating and self-regulating under conditions of continuous, but not uniform, sediment supply; stable, but not static eustatic sea level change, and continuous, slow basinal subsidence (Frazier, 1967;Fisher,1969; Brown, 1969; Asquith, 1974; Balsey, 1982).

CHAPTER 5 STRUCTURE AND HYDROCARBON DISTRIBUTION

5.1.1 Regional Structural Attitude of the Mannville Group

The geographical setting of the study area and its relation to some of the major structural elements of the Lower Cretaceous Western Canadian Sedimentary Basin is illustrated in Figure 5.1. The structural contours on the top of the Mannville Group (Fig. 5.2) illustrate the regional structural attitude of the Mannville Group strata. Two prominent features or structural attitudes are particularly evident in the vicinity of the study area. The first is the regional dip of the Mannville Group. To the north, south and west of the study area, Mannville Group strata gently dip (approximately 1.7-2.0 m/km) to the southwest. The second major feature, which is particularly significant within the study area, is an elongate north-northeast trending trough or syncline.

This regional structural feature coincides with the present edge of contiguous Middle Devonian Prairie Evaporite salt deposits (Haidl, 1984). The narrow linear geometry of this feature and its coincidence with the edge of contiguous salt deposits suggest that it is a collapse feature created by solution of the Prairie Evaporite Formation (De Mille *et al.*, 1964; Vigrass, 1965, 1967, 1968; Orr *et al.*, 1977; Ranger, 1983; Wilmot and Oliver, 1983; Haidl, 1984; Ranger and Pemberton, 1988). This salt solution trough is a regional feature which extends beyond the study area northwest into the Athabasca deposit and southeast into the Lloydminster area. Superposition of this salt solution trough upon regional dip produces a distinct narrow ridge which is particularly prominent within the central portion of the study area (Figs. 5.3). The trend of this ridge, after the affects of regional dip have been removed is depicted on the third order trend of structural contours on the unconformity surface (Fig. 5.4). The presence of this ridge has considerable influence on the distribution of hydrocarbons within the oil sands areas of eastern Alberta and western Saskatchewan. The main Cold Lake oil sands deposit is situated on the crest of this feature while the majority of the Athabasca deposit lies across it. The influence of the ridge on the distribution of hydrocarbons is particularly significant in the vicinity of the

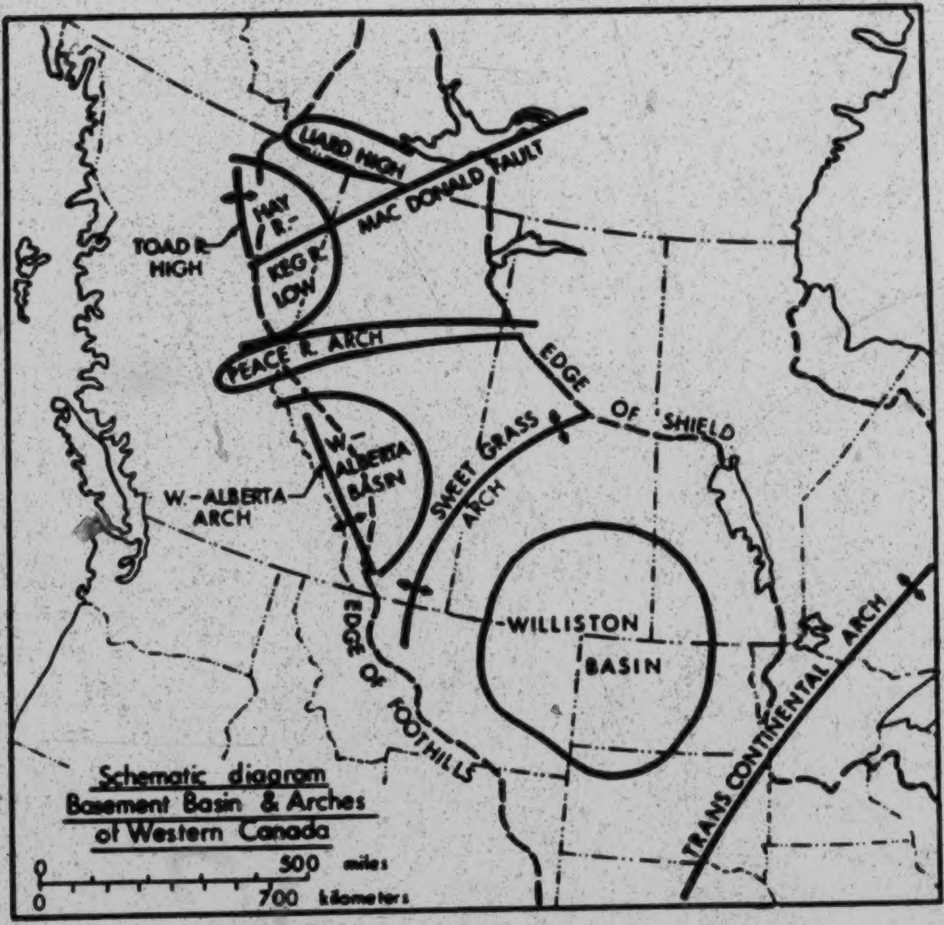


Figure 5.1 Major stuctural elements of the Lower Cretaceous Western Canadian Sedimentary Basin (From Stelck, 1975).

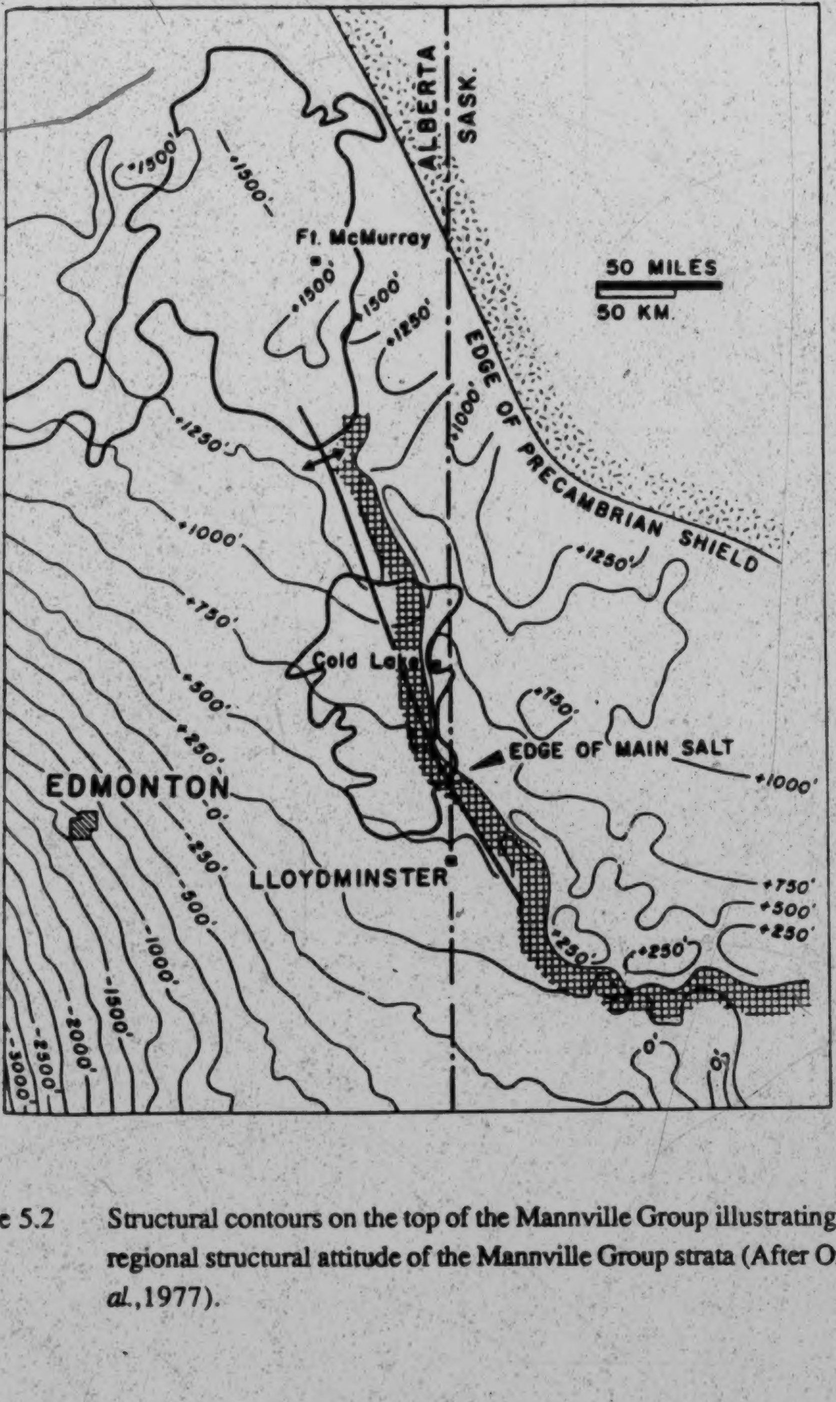
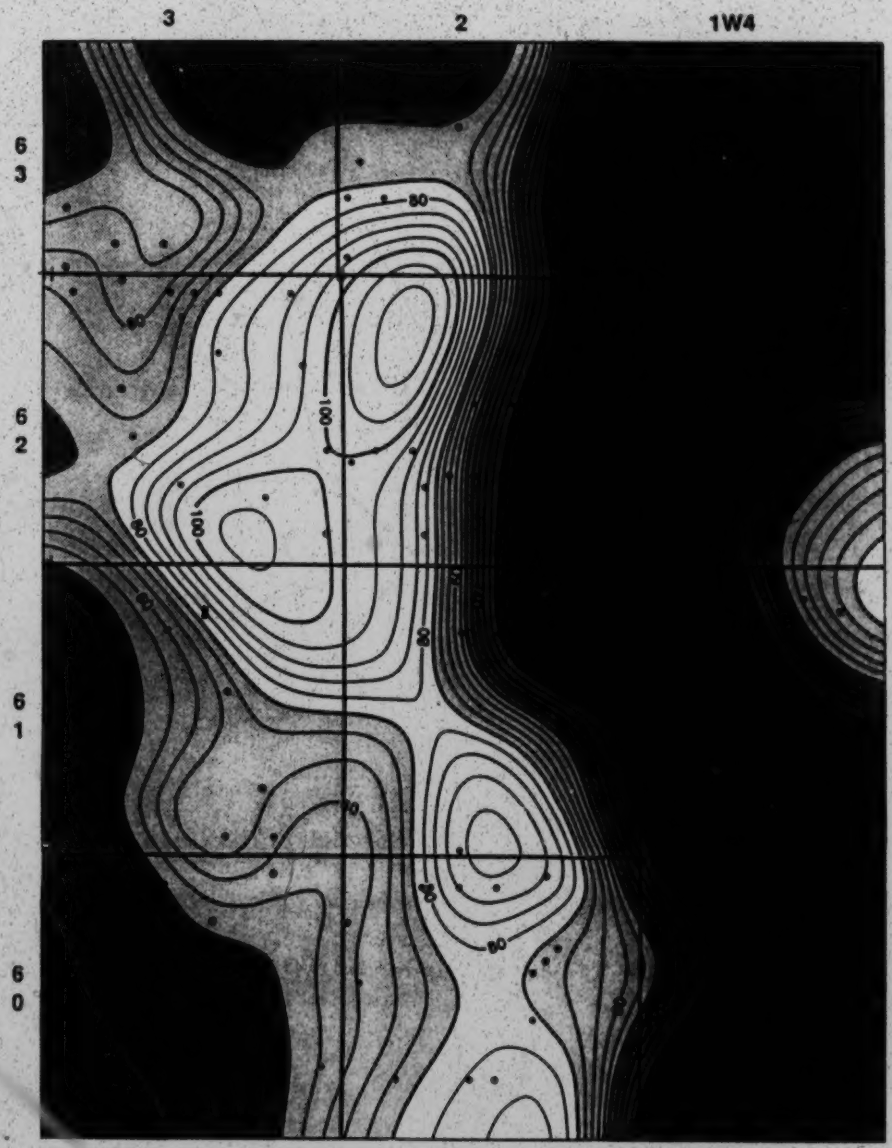


Figure 5.2 Structural contours on the top of the Mannville Group illustrating the regional structural attitude of the Mannville Group strata (After Orr *et al.*,1977).



STRUCTURAL CONTOUR MAP ON THE TOP OF THE
SUB-CRETACEOUS UNCONFORMITY SURFACE
5 METER CONTOUR INTERVAL
DATUM : SEA LEVEL

Figure 5.3 Structural contours on the top of the sub-Cretaceous unconformity.

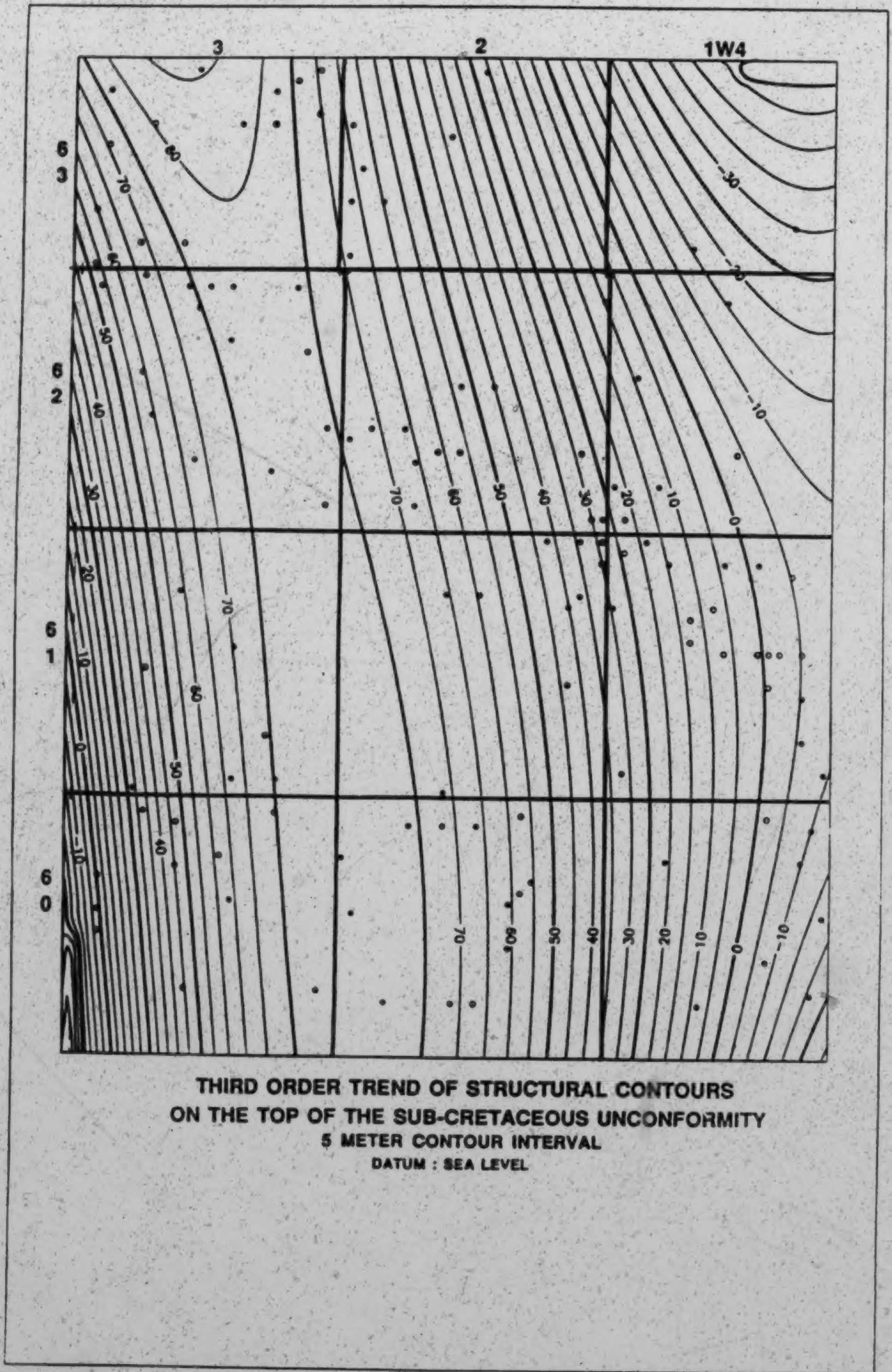

3
2
1W4
6
3
6
2
6
1
6
0
70
60
-30
-20
-10
0
10
20
30
40
50
60
70
-10
THIRD ORDER TREND OF STRUCTURAL CONTOURS
ON THE TOP OF THE SUB-CRETACEOUS UNCONFORMITY
5 METER CONTOUR INTERVAL
DATUM : SEA LEVEL

Figure 5.4 Third order trend of the structural contours on the top of the sub-Cretaceous unconformity.

study area and will be discussed in detail in the latter portion of this chapter.

5.1.2 Local Structure

Within the vicinity of the study area, the McMurray Formation abruptly rests upon carbonates of the Woodbend and Beaverhill Lake Groups. Many authors have discussed the influence paleotopography on the sub-Cretaceous unconformity surface has had on Mannville Group sedimentation (Williams, 1963; Vigrass, 1967; Jardine, 1974; Orr *et al.*, 1977; Mossop *et al.*, 1980; Ranger, 1983; Ranger and Pemberton, 1988; Putnam, 1988). Paleotopography of the unconformity surface can be modelled by creating an isopach of the Mannville Group (Fig. 5.5). The isopachs of the Mannville Group exhibit considerable variation across the trend of the salt solution trough and ridge (up to 110m in the central portion of the study area). The isopachs of the McMurray Formation display a similar overall pattern (Fig. 5.6). Thickening of the McMurray Formation and the Mannville Group within the vicinity of the salt solution trough suggests that solution-related subsidence was active prior to or during Mannville Group deposition and may have occurred contemporaneously with erosion upon the sub-Cretaceous unconformity (Ranger and Pemberton, 1988). Thus, it appears that the topography of the unconformity surface significantly influenced McMurray Formation deposition and that the salt solution trough was a site of preferential sediment accumulation during the initial stages of McMurray Formation deposition. Furthermore, the development of both thickened Mannville Group and McMurray Formation successions suggest that solution related subsidence was active during the deposition of the Mannville Group.

This pattern of preferential sedimentation inferred for the McMurray Formation is not readily apparent in the Clearwater Formation. Although the isopachs of the Clearwater Formation (Fig. 5.7) display some thickening in the vicinity of the salt solution trough, overall the Clearwater Formation isopachs exhibit a planar, tabular geometry. This suggests that the paleotopography of the unconformity surface did not significantly influence the

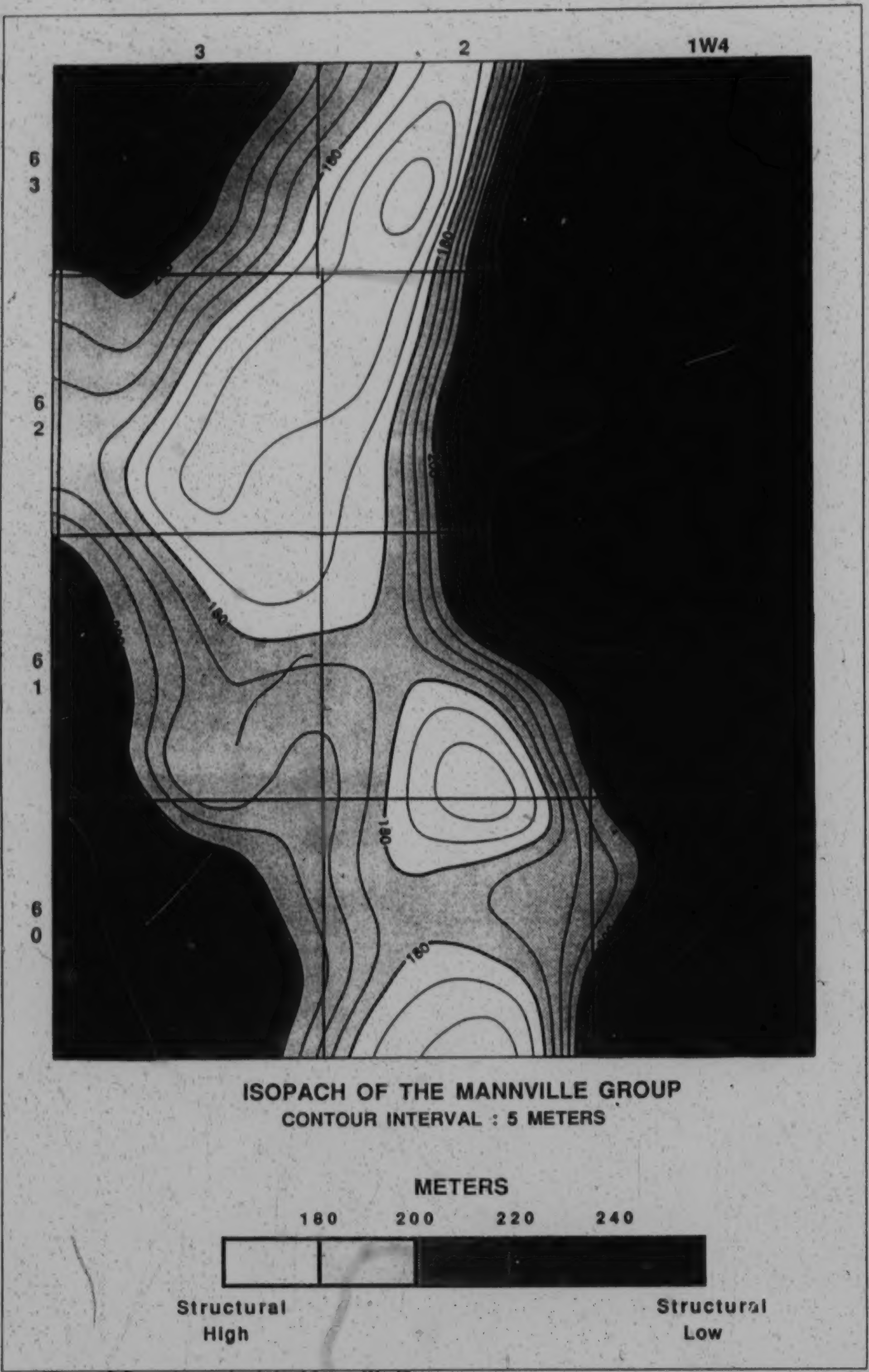


Figure 5.5 Isopach of the Mannville Group.

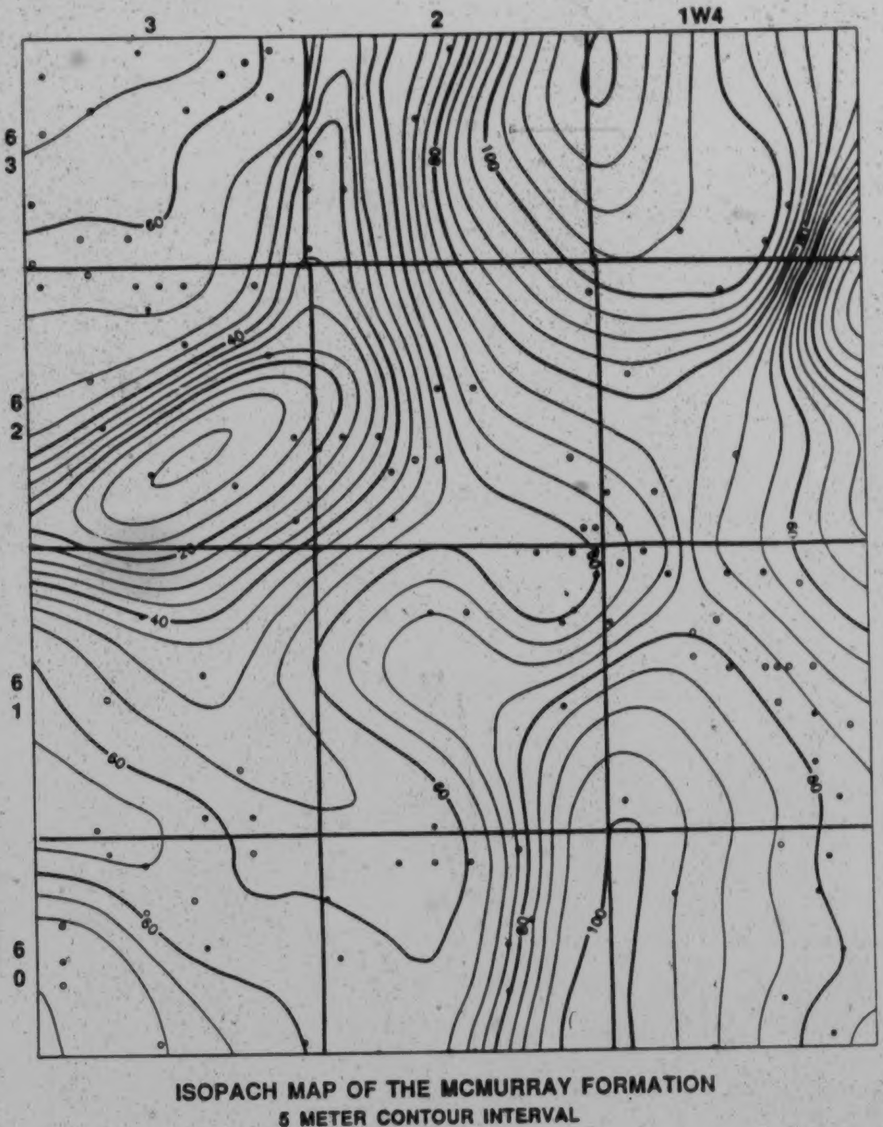


Figure 5.6 Isopach map of the McMurray Formation.

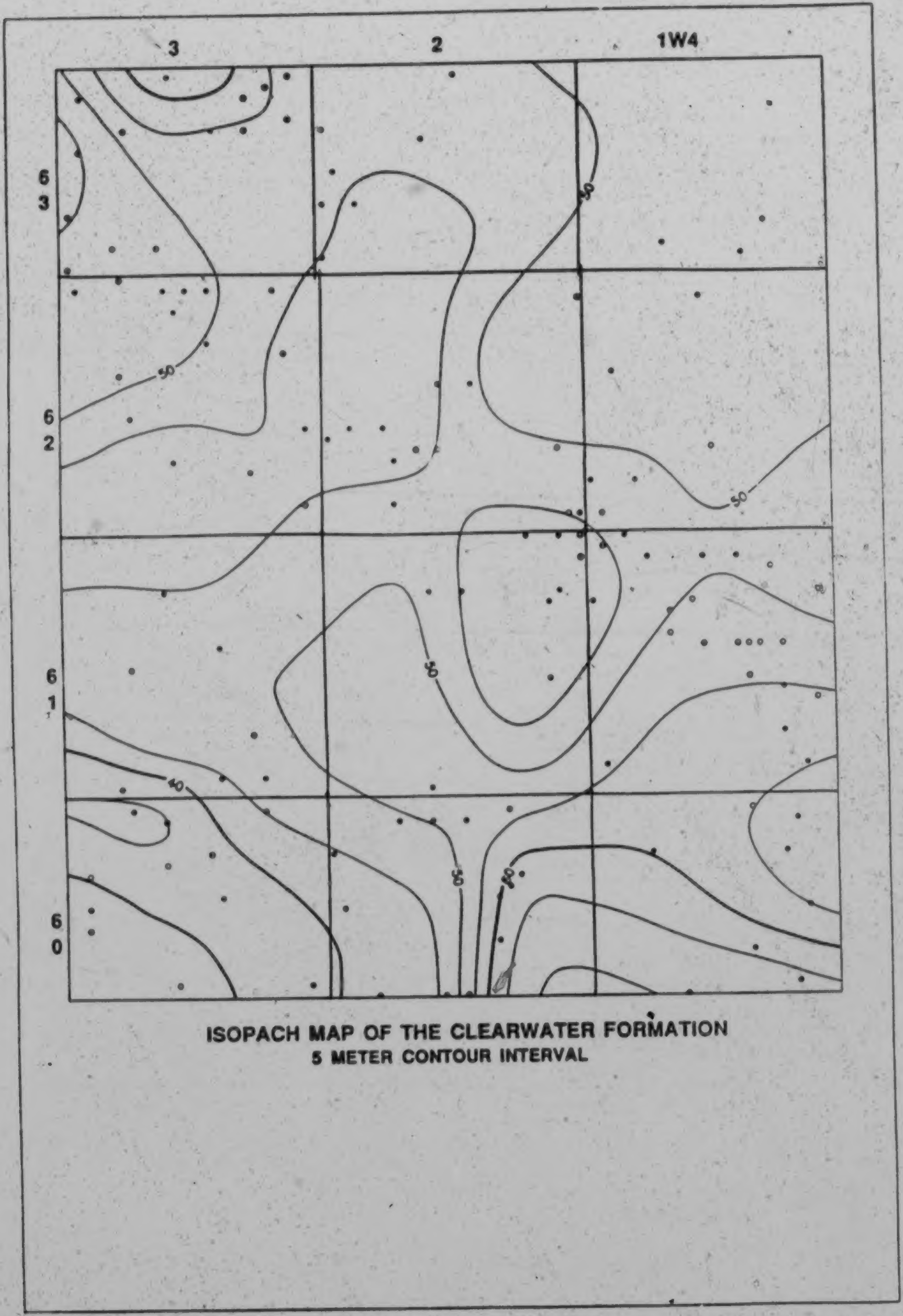


Figure 5.7 Isopach map of the Clearwater Formation.

deposition of the Clearwater Formation. Rather, most of the topographic relief developed on the unconformity surface had been preferentially filled with McMurray Formation sediments, and any remaining structural relief present at the close of McMurray Formation deposition was accommodated during deposition of the Clearwater Formation. The isopach map of the Grand Rapids Formation (Fig. 5.8) displays a similar planar, tabular geometry with only slight thickening in the vicinity of the salt solution trough. Similarly, isopach maps of the individual lithosomes and all other Lower Cretaceous horizons display planar, tabular geometries. This uniformity or parallelism of isopachs suggests that the paleotopography developed on the sub-Cretaceous unconformity did not significantly influence sedimentation other than during the initial stages of McMurray Formation deposition. The minor thickening that most isopachs display within the vicinity of the salt solution trough may be related to differential compaction or may imply that there was some active solution related subsidence during the deposition of the remainder of the Mannville Group. Solution-related subsidence active during deposition of the Grand Rapids Formation may have influence the rate of progradation, the rate of transgression, the orientaion and size of channel-fill successions and other factors which influenced the distribution of facies within the Grand Rapids Formation.

5.1.3 Origin of Local Structure

Structural contours on the top of the Clearwater Formation (Fig. 5.9), the Grand Rapids Formation (Fig. 5.10) and the Base of the Fish Scales (Fig. 5.11) all display similar patterns to those depicted by the structural contours on the top of the sub-Cretaceous unconformity (Fig. 5.4). However, as illustrated in the preceding discussion, all post-McMurray Formation isopachs are characterized by planar, tabular geometries. This suggests that although there is evidence of solution-related subsidence contemporaneous with the formation of the sub-Cretaceous unconformity and deposition of the McMurray Formation, the present-day structural attitude of the Mannville Group strata, depicted by the structural contour maps, is primarily a result of a deformational event which post-dates deposition of the Mannville Group. Isopachs from the top of the Mannville Group to the

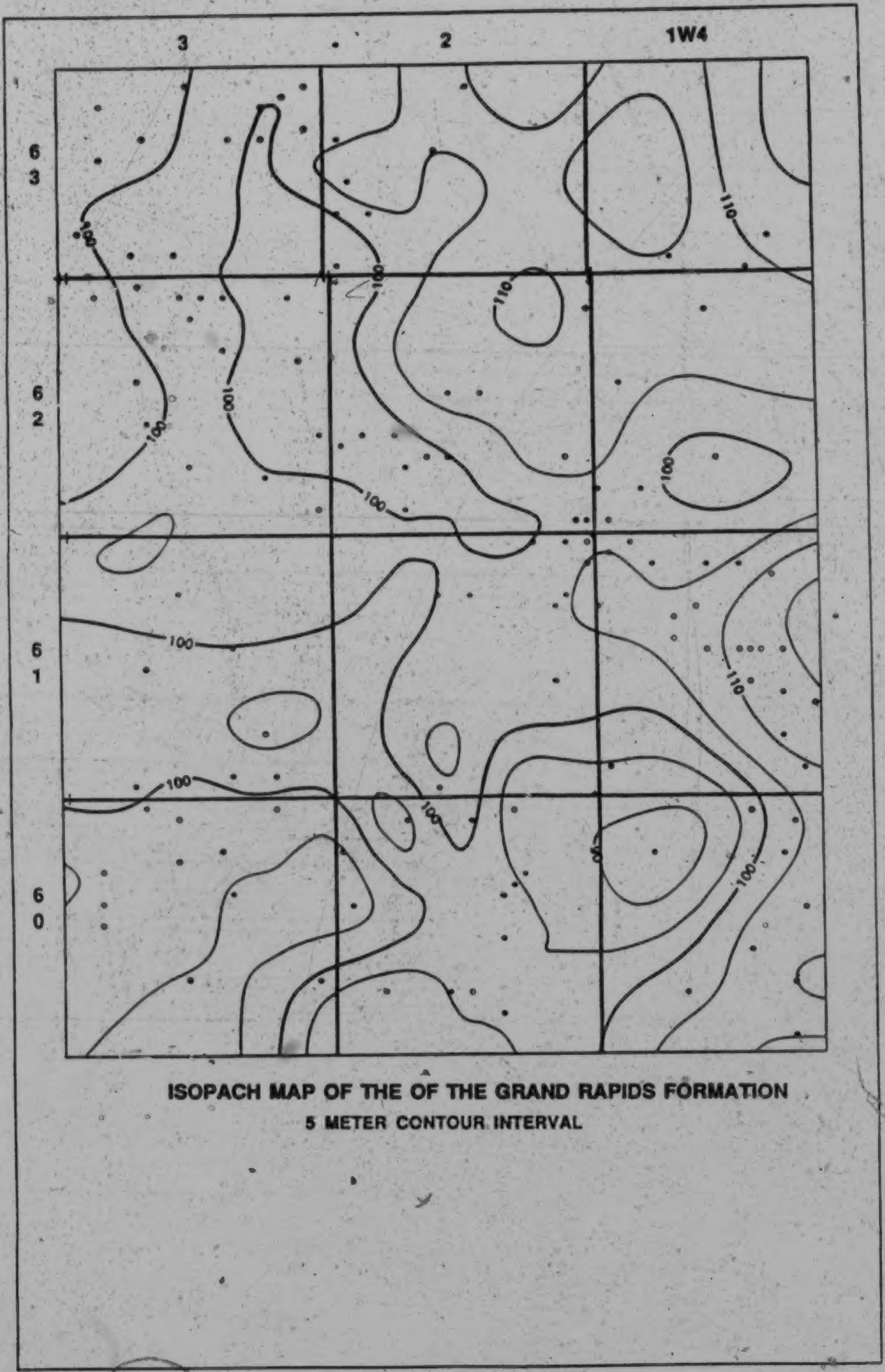


Figure 5.8 Isopach of the Grand Rapids Formation.

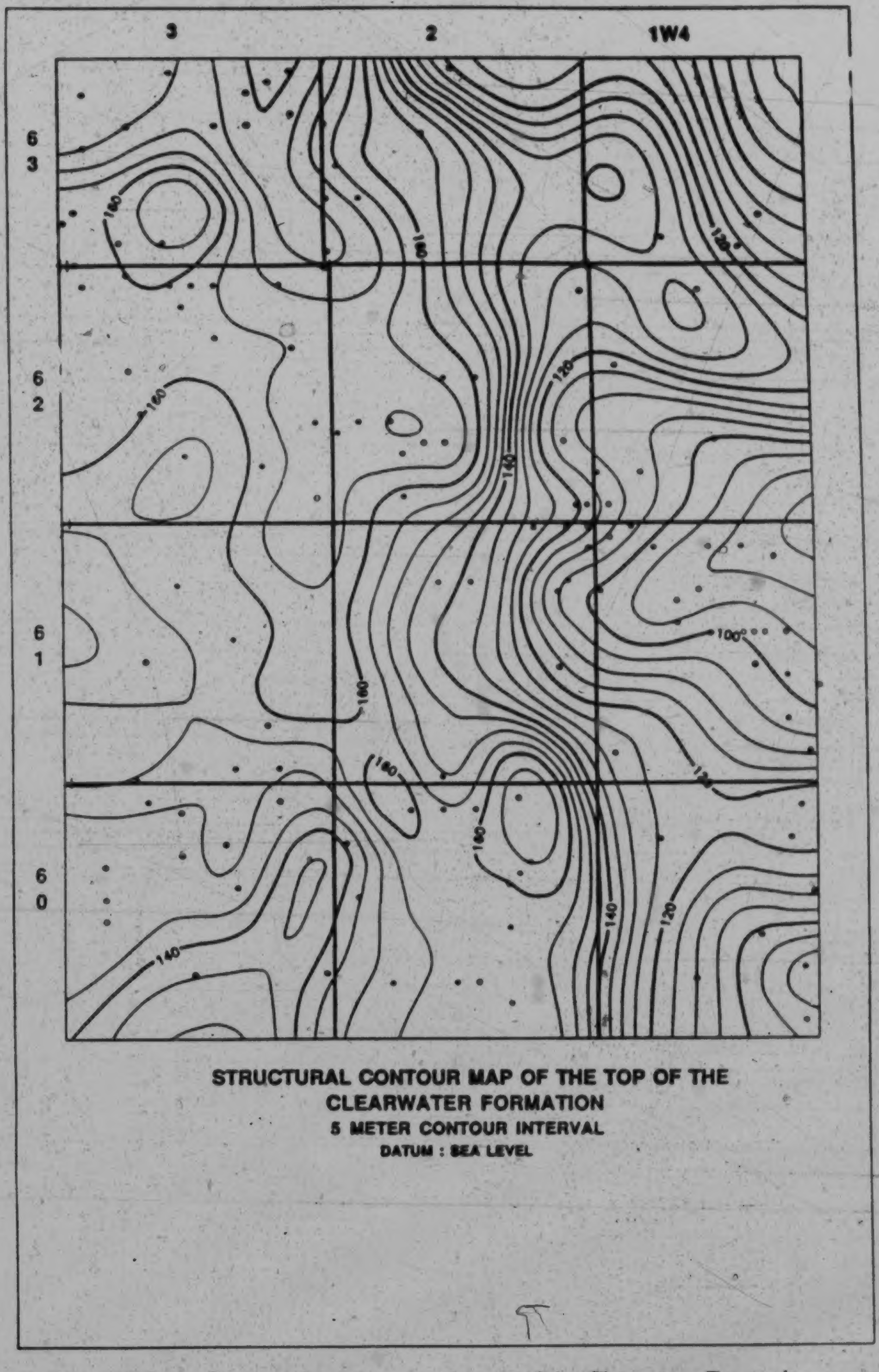
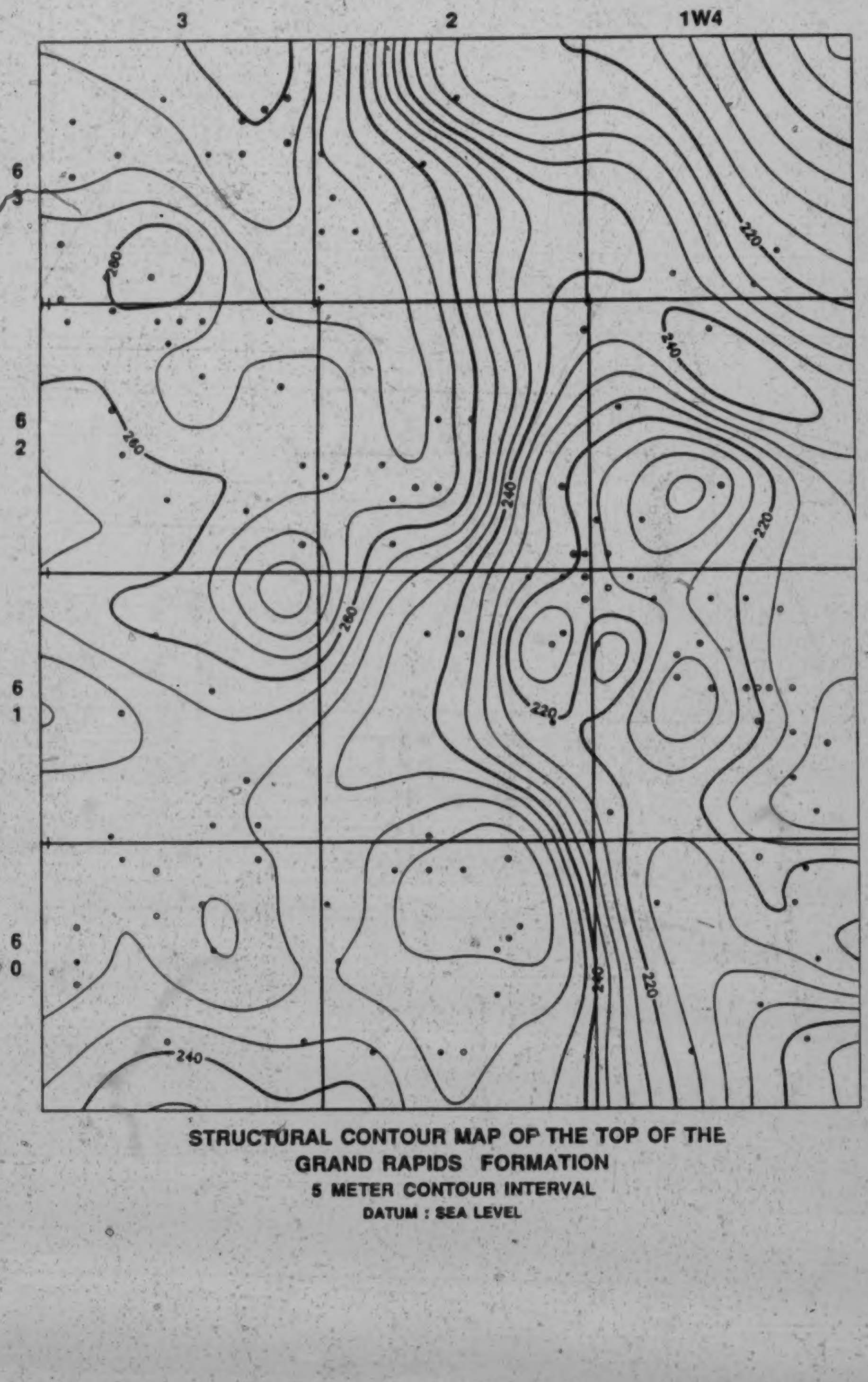
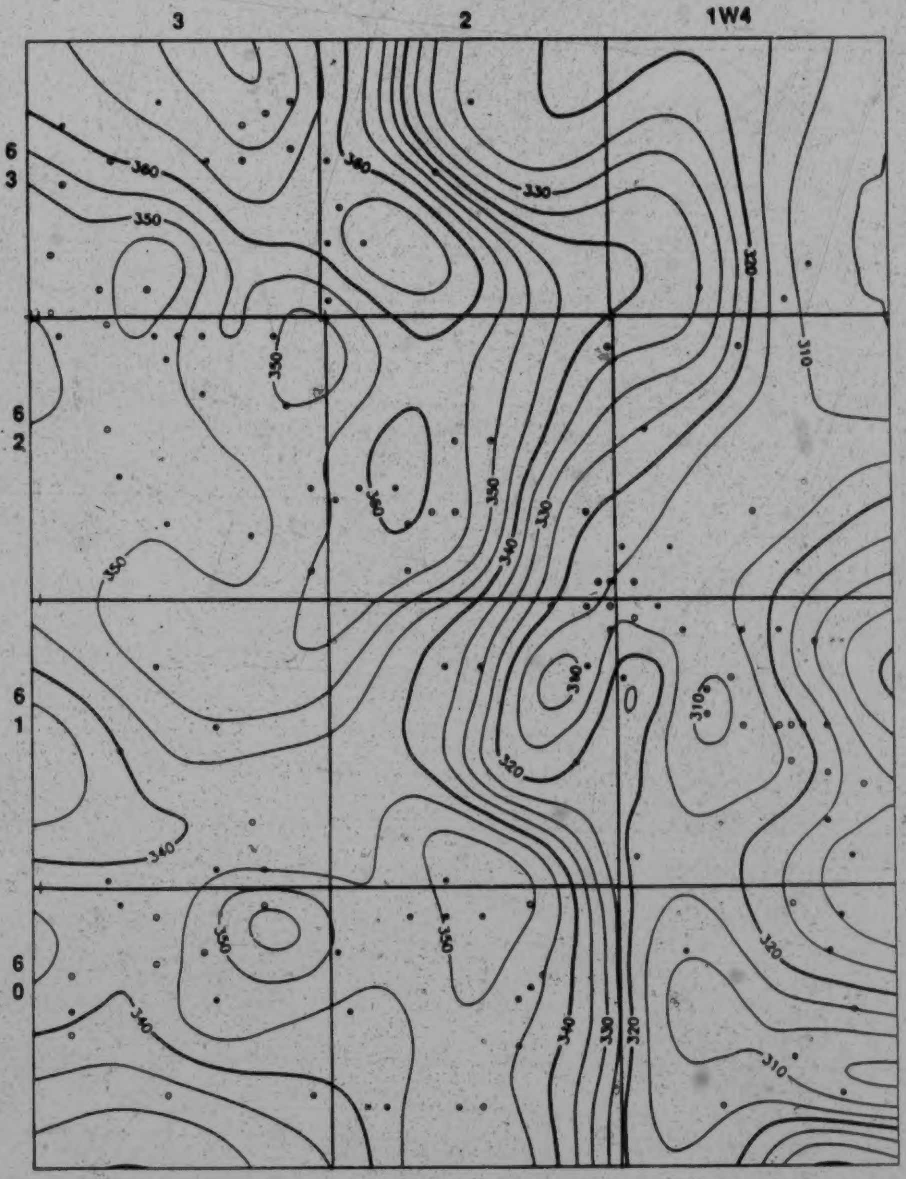


Figure 5.9 Structural contours on the top of the Clearwater Formation.



STRUCTURAL CONTOUR MAP OF THE TOP OF THE GRAND RAPIDS FORMATION
5 METER CONTOUR INTERVAL
DATUM : SEA LEVEL

Figure 5.10 Structural contours on the top of the Grand Rapids Formation.



STRUCTURAL CONTOUR MAP OF THE TOP OF THE BFS
5 METER CONTOUR INTERVAL
DATUM : SEA LEVEL

Figure 5.11 Structural contours on the Base of the Fish Scales

Base of Fish Scales (Fig. 5.12) and to the top of Second White Speckled Shale display a planar, tabular geometry without evidence of significant thickening across the trend of the salt solution trough. This suggests that the present structural attitude of the Mannville Group strata observed within the study area is a result of a salt solution event which post-dates deposition of the Second White Speckled Shale. De Mille *et al.* (1964) suggested salt solution of the Prairie Evaporite Formation initiated during the Late Devonian and occurred episodically, with maximum solution occurring contemporaneous with erosion of the sub-Cretaceous unconformity and following deposition of the Second White Speckled Shale. There is direct evidence of the latter two episodes of salt solution; however, the event which post-dates deposition of the Second White Speckled Shale appears to have exhibited the most significant influence on the present-day structural attitude of the Mannville Group strata within the study area.

5.2 Distribution of Hydrocarbons

5.2.1 Introduction

The Grand Rapids Formation within the Cold Lake oil sands area is estimated to contain 19, 050 x 10^6 m^3 (120 billion barrels) of oil-in-place. To date, only a small volume of the possible oil and gas reserves associated with the Grand Rapids Formation has been recovered. Within the study area, production has been restricted to the recovery of gas from the Colony or upper Grand Rapids formations (GR_6 lithosome).

As discussed within Chapter 4, the Grand Rapids Formation consists of a succession of transgressive-progradational cycles which record local shoreline response to fluctuations in relative sea level, subsidence and sediment supply. These cycles are arranged into six flooding surface-bounded depositional units termed lithosomes, each of which records an interval of deltaic sedimentation. Since the Grand Rapids Formation has been subjected to shallow burial and minimal post-depositional diagenesis, the reservoir characteristics of each individual lithosome reflects the primary distribution of facies present

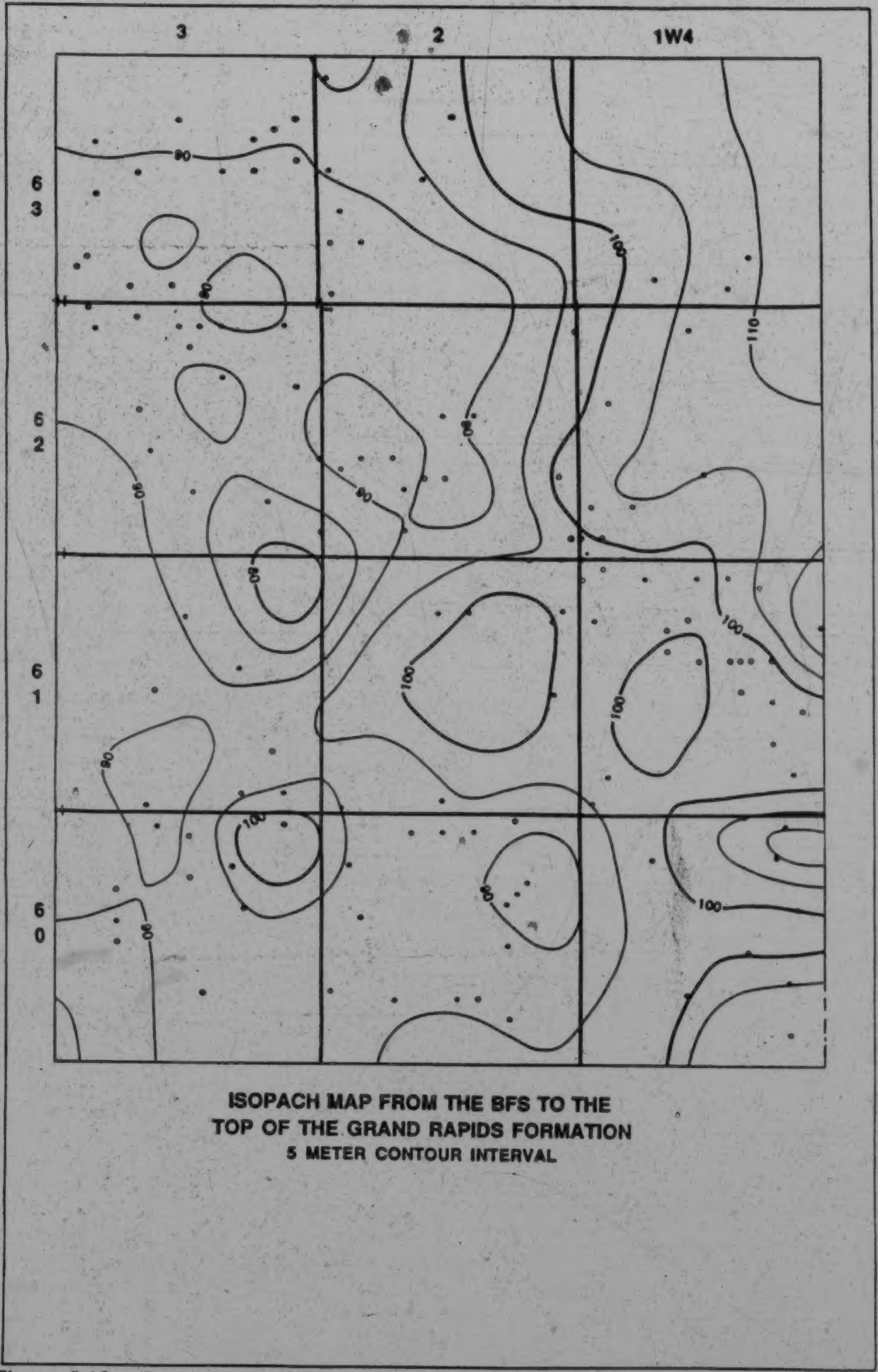

3
2
1W4
6
3
6
2
6
1
6
0
90
100
110
100
100
100
100
ISOPACH MAP FROM THE BFS TO THE
TOP OF THE GRAND RAPIDS FORMATION
5 METER CONTOUR INTERVAL

Figure 5.12 Isopach map from the Base of the Fish Scales to the top of the Mannville Group (top of Grand Rapids Formation).

during that particular interval of sedimentation. Thus reservoir parameters such as porosity and permeability are for the most part related to depositional processes. Given the sedimentological model proposed, the Grand Rapids Formation can be viewed to comprise multiple, dynamically separate reservoirs. The key to this reservoir model is the brackish to marine mudstones which overlie the transgressive flooding surfaces. These mudstones are considered to be essentially impervious to fluids and therefore prevent communication between the reservoir sandstones of different lithosomes. This proposed reservoir model for the Grand Rapids Formation is based primarily on sedimentological observations; additional subsurface and reservoir engineering data is necessary to confirm the validity of this proposed model.

5.2.2 Methodology

The following suite of net pay isopach maps illustrates the distribution of potential reservoir strata. Potential reservoir strata were defined as those strata of sufficient quality and bitumen saturation to potentially produce hydrocarbons. These strata were identified and mapped by calibrating core analysis derived weight percent bitumen saturation values with the response of the deep induction curve. Deep induction values between 8 and 10 ohm-m corresponded with core derived values of 8 weight percent bitumen saturation. Deep induction log cut-off values were then utilized to map the distribution of potential reservoir strata within the study area.

5.2.3 Hydrocarbon distribution within the Grand Rapids Formation

GR_1 Lithosome

The GR_1 lithosome comprises a complete regressive succession in which shelf and shoreface deposits are overlain by fluvial-distributary channel-fill deposits. Typically, the lowermost shoreface sandstones, despite excellent porosity and permeability characteristics, are commonly water-saturated and only locally represent viable potential reservoir strata.

The fluvial-distributary channel-fill sandstones constitute the majority of the potential reservoir strata associated with the GR_1 lithosome.

Within the study area, two areas, the northwest and the southwest, contain significant quantities of bitumen-saturated sandstone (Fig. 5.13). Volumetric reserve calculations suggest a possible 624 x 10^6 m^3 of oil-in-place in the GR_1 lithosome. Figure 5.14 illustrates the strong correlation between structure and hydrocarbon distribution within the GR_1 lithosome. The shaded pattern outlines areas where the thickness of bitumen-saturated sandstone exceeds 5 meters and the bitumen saturation exceeds 8 weight percent. The majority of the potential reservoir strata are associated with the structurally highest portions of the ridge or closed structural highs located on the ridge or the flanks of the ridge. Although sandstone with good porosity and permeability characteristics are readily available (Fig 5.14b), the majority of the sandstones within the eastern portion of the study area are water-saturated. Strata located on the flanks of the ridge (*eg*. Twp. 60, Rge. 3 and Twp. 63, Rge. 2) coincide with the location of the thickest accumulations of porous sandstone. However sandstones located in this area are also characterized by thick bottom water zones. Thus it appears that within the GR_1 lithosome the thickness of bitumen-saturated sandstone is related to the availability of porous and permeable sandstone and structural elevation, with structural elevation exerting the most significant influence on the quantity and continuity of pay.

GR_2 Lithosome

The GR_2 lithosome comprises one or two stacked progradational delta front successions, which locally have been incised into and replaced by narrow, linear distributary channel-fill complexes. Both the delta front and distributary channel-fill sandstones represent potential reservoir strata in the GR_2 lithosome.

Figure 5.15 illustrates the distribution of potential reservoir quality strata within the GR_2 lithosome. The GR_2 lithosome is estimated to contain 663 x 10^6 m^3 of possible oil in

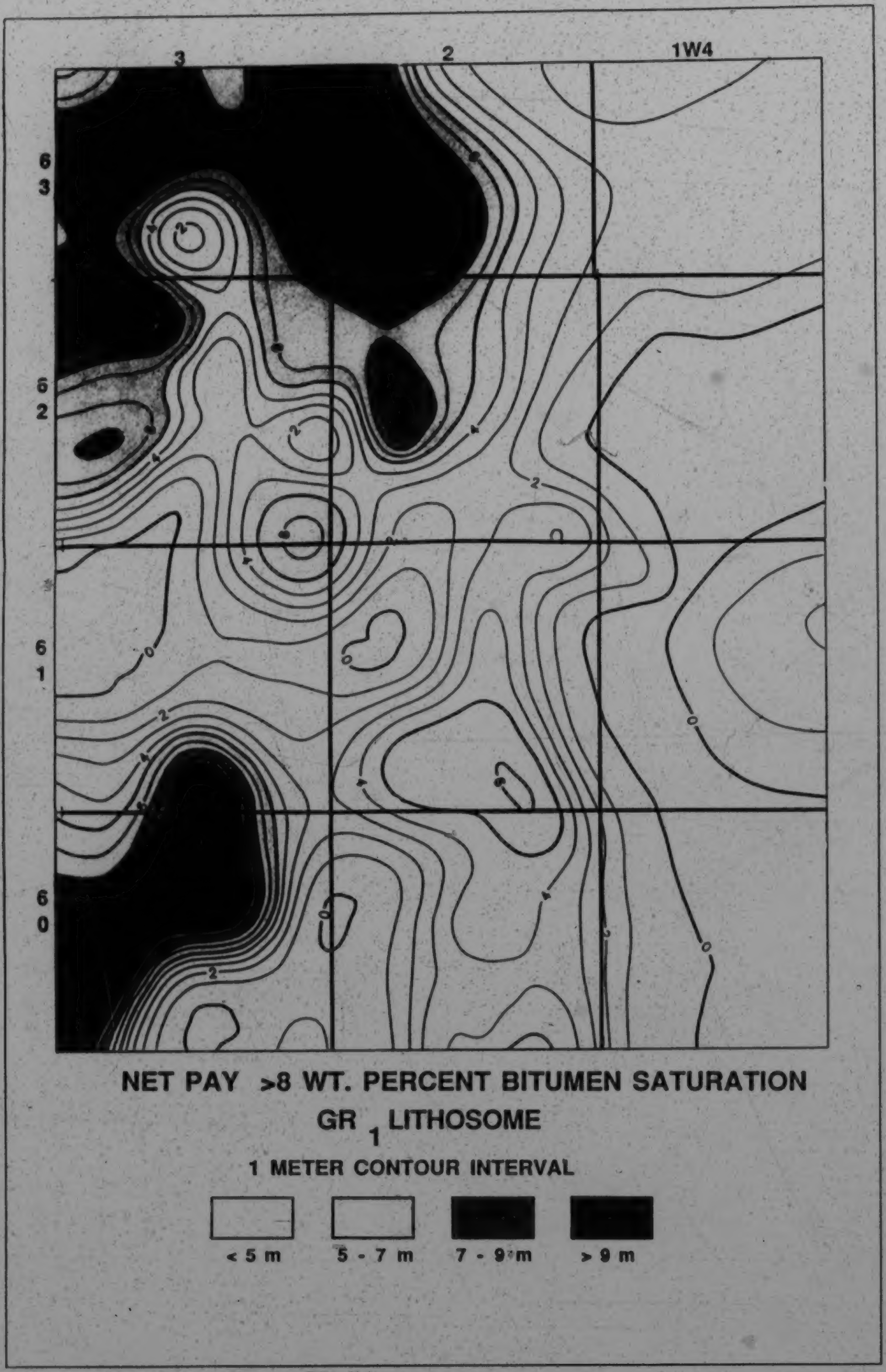


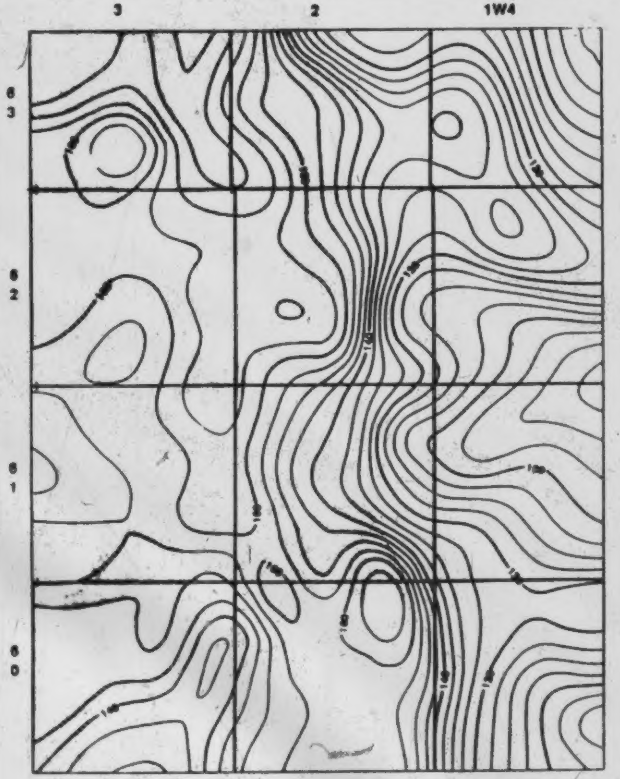
Figure 5.13 Net pay GR_1 lithosome.

Figure 5.14

Structural and geological controls on hydrocarbon distribution within the GR_1 lithosome

a) Outline of potential hydocarbon pools superimposed on structural contours on the top of the Clearwater Formation. The shaded pattern outlines areas where the thickness of bitumen saturated sandstone exceeds 5 meters and the relative bitumen saturation exceeds 8 weight percent.

b) Net sandstone map GR_1 lithosome.

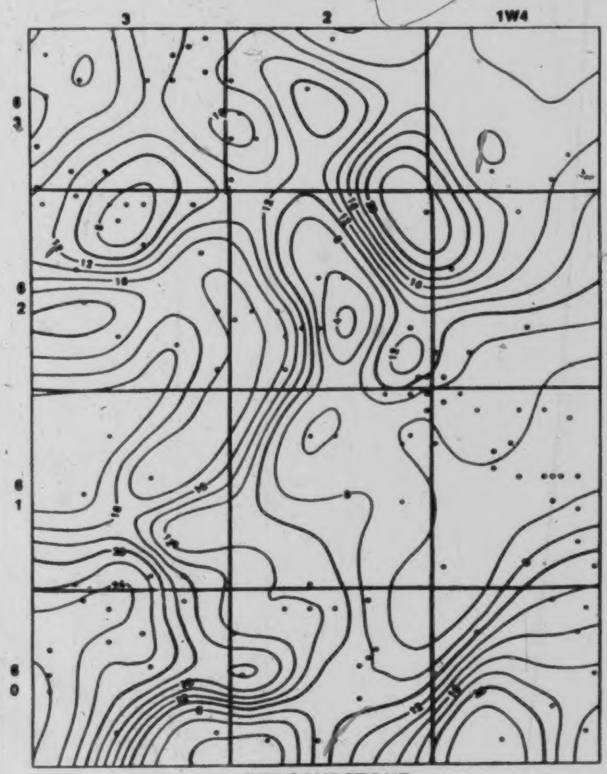


BITUMEN SATURATED SANDSTONE

DISTRIBUTION MAP

GR_1 LITHOSOME

A



NET SANDSTONE

GR_1 LITHOSOME

2 METER CONTOUR INTERVAL

B

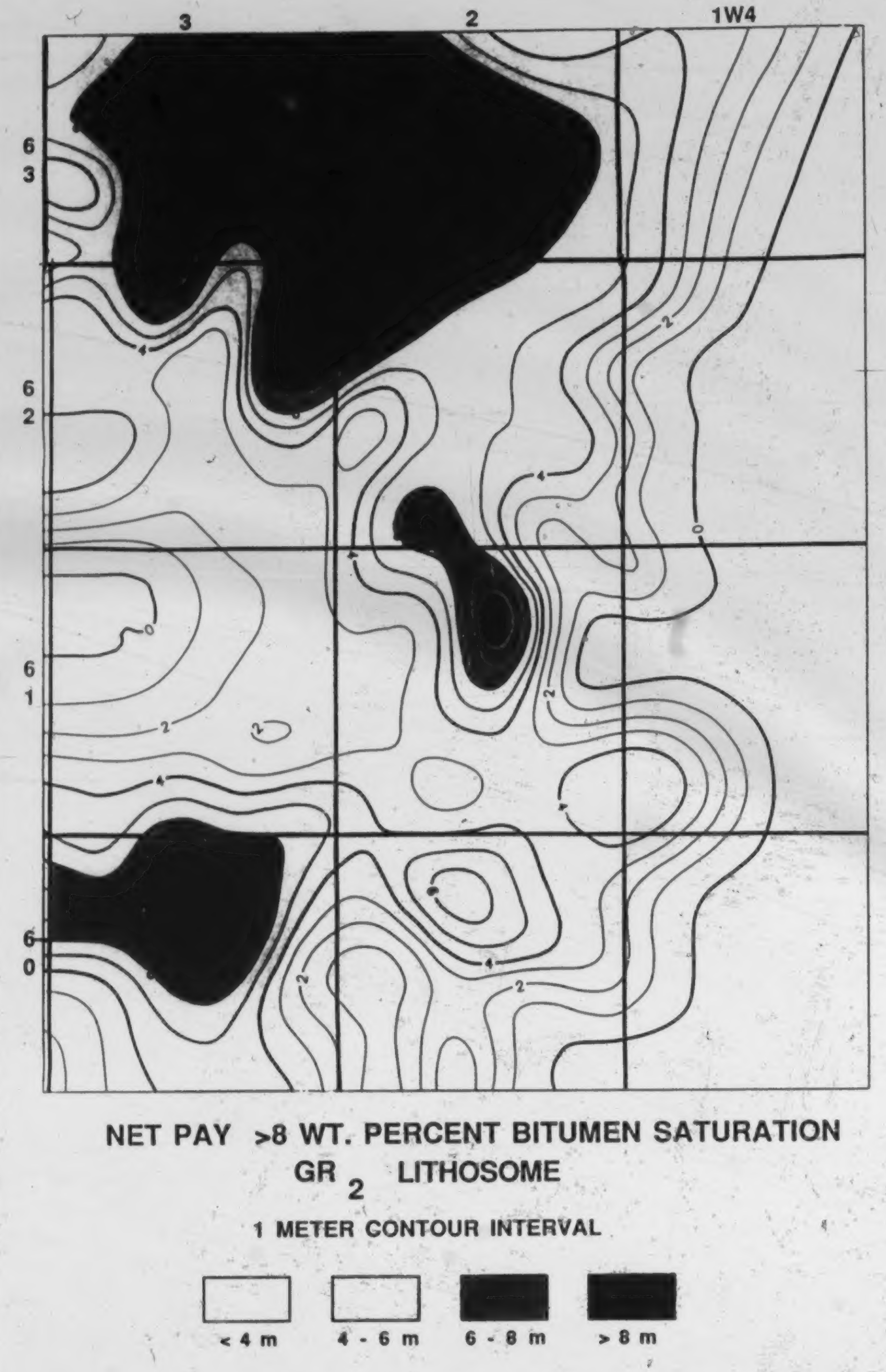


Figure 5.15 Net pay GR_2 lithosome.

place. The pattern of hydrocarbon distribution is very similar to that observed within the GR_1 lithosome, in which structural elevation influences the thickness of the bitumen-saturated column. Porous and permeable reservoir quality sandstone is available throughout the study area; however, the majority of the bitumen-saturated sandstone is concentrated on the structurally highest portions of the ridge and within closed structural highs developed along the ridge axis (Fig. 5.16). Potential reservoir strata are also found trapped in structural culminations along the eastern margin of the ridge. Structural influence on the distribution of hydrocarbons is also suggested by the close parallelism of structural contours and net pay isopachs. This relationship is particularly evident in the vicinity of the salt solution trough where the zero net pay isopach follows the trend of the salt solution trough.

GR_3 Lithosome

The GR_3 lithosome displays a depositional pattern similar to that of the GR_2 lithosome. The principal depositional units consist of delta front sandstones which have been incised and replaced by distributary channel-fill deposits. Both the delta front and the distributary channel-fill sandstones have good reservoir potential. However, due to their thickness, the majority of the possible reserves are associated with the distributary channel-fill sandstones. In structurally elevated areas, the delta front sandstones may locally represent attractive reservoirs, particularly where thick delta front sandstones are developed. The upper portion of the GR_3 lithosome contains the first significant accumulations of delta plain deposits. These delta plain deposits are dominated by interdistributary bay-fill mudstones with minor amounts of crevasse splay and crevasse channel sandstones. Locally, these sandstones may have good porosity and permeability characteristics but their lateral continuity is limited. As such, the crevasse splay and crevasse channel sandstones in the GR_3 lithosome are not considered to have significant reservoir potential.

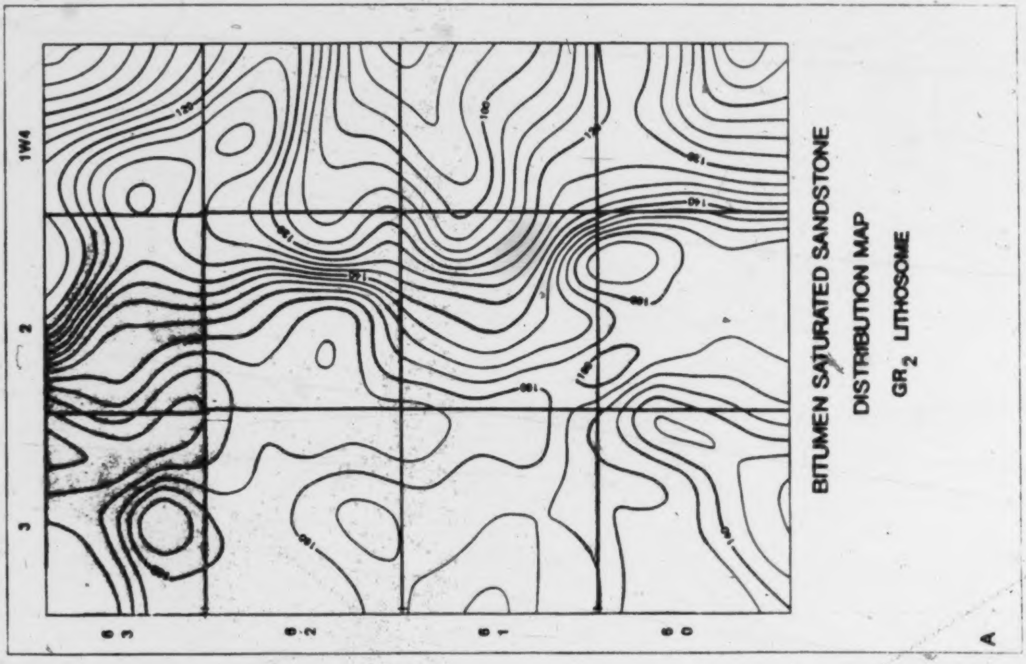
Figure 5.17 illustrates the distribution of reservoir quality bitumen-saturated

Figure 5.16

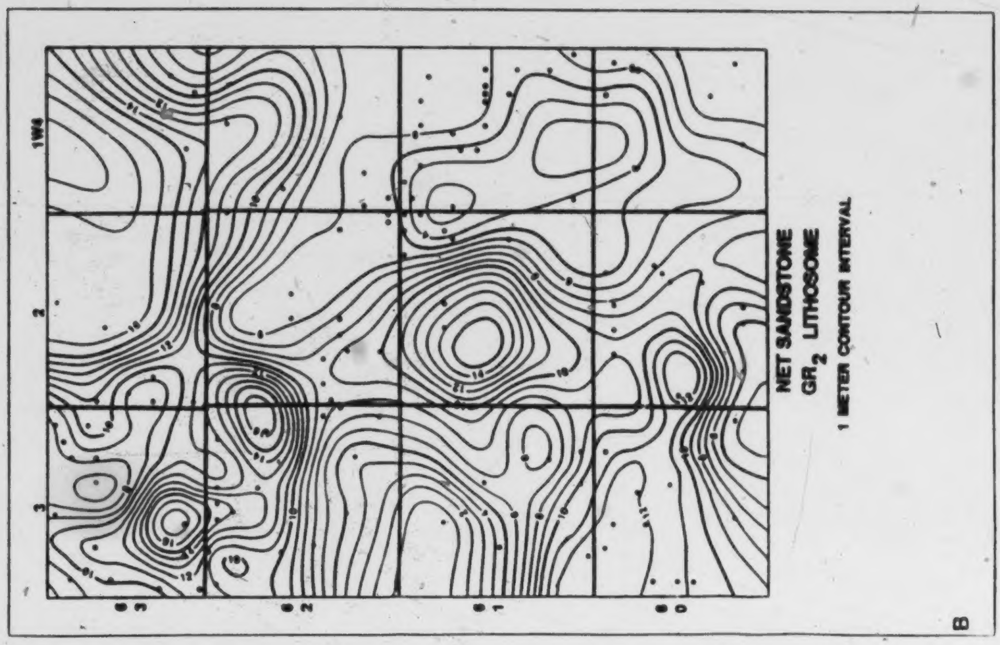
Structural and geological controls on hydrocarbon distribution within the GR_2 lithosome

a) Outline of potential hydocarbon pools in the GR_2 lithosome superimposed on structural contours on the top of the Clearwater Formation. The shaded pattern outlines areas where the thickness of bitumen saturated sandstone exceeds 5 meters and the relative bitumen saturation exceeds 8 weight percent.

b) Net sandstone map GR_2 lithosome.



BITUMEN SATURATED SANDSTONE
DISTRIBUTION MAP
GR_2 LITHOSOME



NET SANDSTONE
GR_2 LITHOSOME
1 METER CONTOUR INTERVAL

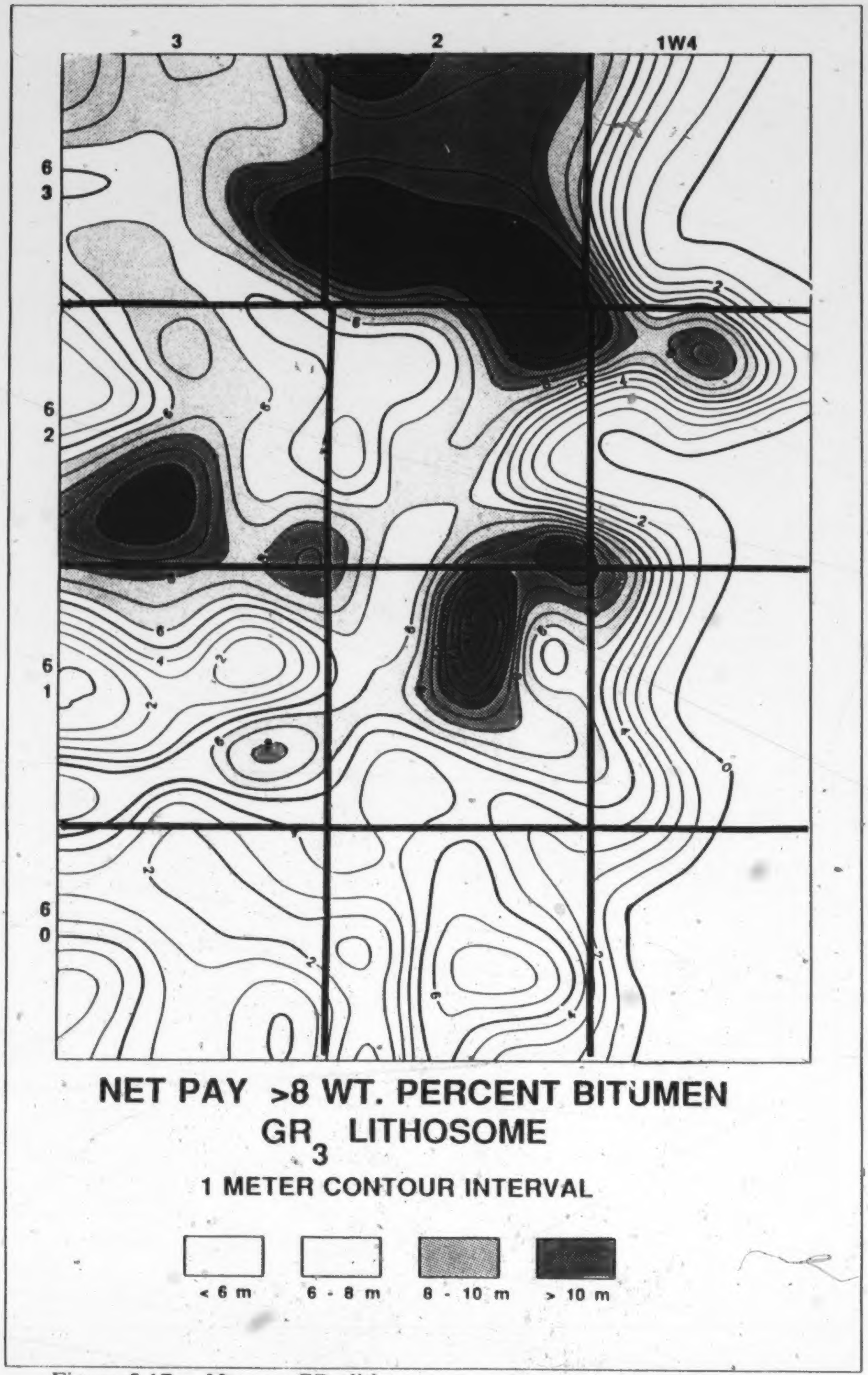


Figure 5.17 Net pay GR_3 lithosome.

sandstones in the GR_3 lithosome. Based on volumetric reserve calculations, the GR_3 lithosome is estimated to contain 774 x 10^6 m^3 of possible oil-in-place. The correlation between hydrocarbon distribution and structural attitude observed within the GR_1 and GR_2 lithosomes is not readily apparent within the GR_3 lithosome. Hydrocarbon distribution within the GR_3 lithosome appears to be both structurally and stratigraphically influenced (Figure 5.18). The majority of the reserves are concentrated in a north-northwest trending distributary channel complex. In the central portion of the study area (Twp. 61, Rge. 2), bitumen is concentrated on the downdip side of the distributary channel complex along the eastern margin of the ridge. In the northern portion of the study area (Twp. 62, Rges. 1 and 2 and Twp. 63, Rge. 2), bitumen-saturated distributary channel-fill sandstones trend across the salt solution trough. Here, structural relief is in excess of 75 m, however bitumen saturation remains relatively uniform. This suggests that stratigraphic or geologic factors contribute the greatest influence on hydrocarbon distribution. Some structural influence is suggested by the increased thickness of bottom water zones in the structurally low-lying areas.

GR_4 Lithosome

The GR_4 lithosome is characterized by extensive tidally-influenced distributary channel or estuarine deposition. Two principal depositional units were recognized within the GR_4 lithosome: interdistributary bay-fill deposits and distributary channel-fill deposits. Many of the channel-fill deposits are very thick (up to 35 m) however, a large proportion of the channel-fill deposits consist of argillaceous, low permeability sandstones and mudstones and therefore do not represent viable reservoir strata. Furthermore, internally the channel-fill deposits are complex and heterogeneous. The bay-fill sandstones, because of their limited lateral and vertical continuity, are considered to have limited reservoir potential.

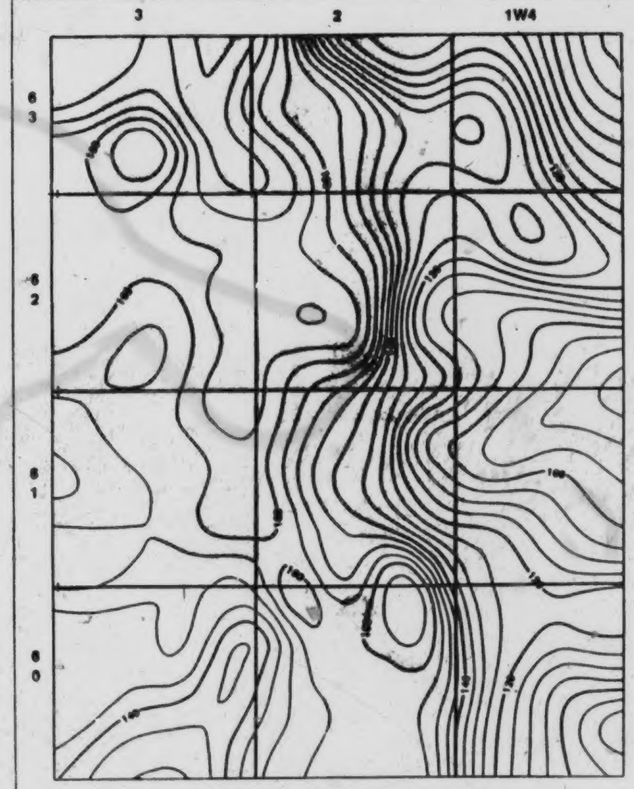
Figure 5.19 illustrates the distribution of strata with greater than 8 weight percent bitumen saturation. Based on volumetric reserve calculations the GR_4 lithosome is estimated to contain 448 x 10^6 m^3 of possible oil-in-place. Within the GR_4 lithosome it

Figure 5.18

Structural and geological controls on hydrocarbon distribution within the GR_3 lithosome

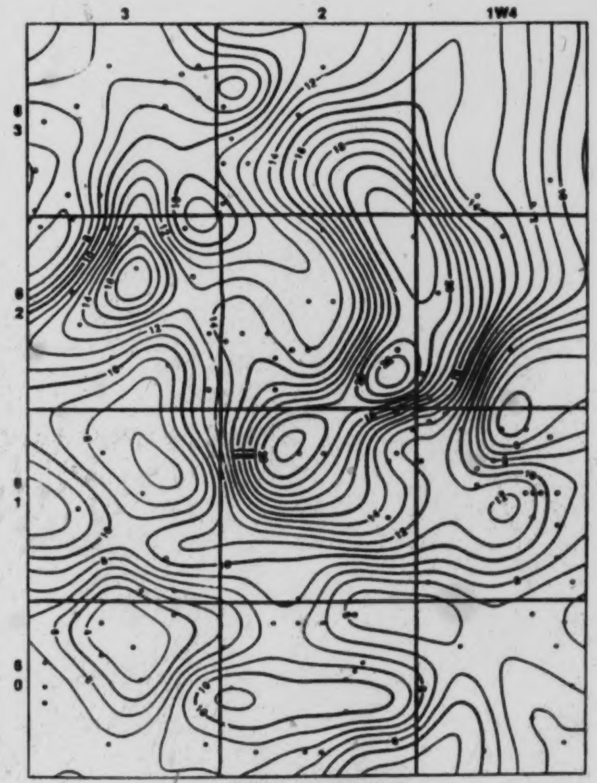
a) Outline of potential hydocarbon pools in the GR_3 lithosome superimposed on structural contours on the top of the Clearwater Formation. The shaded pattern outlines areas where the thickness of bitumen saturated sandstone exceeds 5 meters and the relative bitumen saturation exceeds 8 weight percent.

b) Net sandstone map GR_3 lithosome.



BITUMEN SATURATED SANDSTONE
DISTRIBUTION MAP
GR_3 LITHOSOME

A



NET SANDSTONE
GR_3 LITHOSOME
1 METER CONTOUR INTERVAL

B

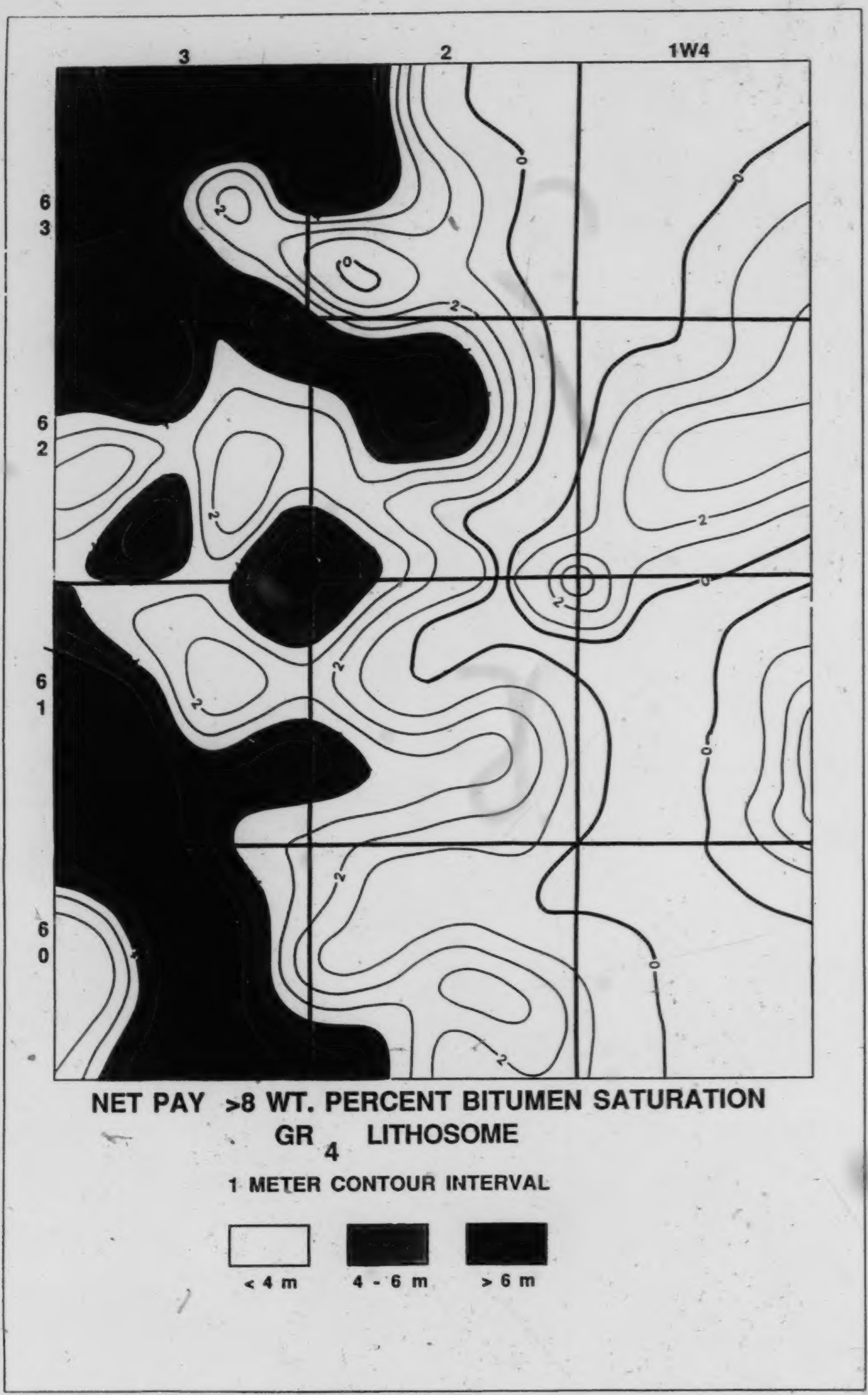


Figure 5.19 Net pay GR_4 lithosome.

appears that both structural and geologic factors influence the distribution of bitumen. A large proportion of the hydrocarbons mapped within the GR_4 lithosome are trapped within closed structural highs located on the ridge (Fig 5.20a). In the southwest portion of the study area (Twp. 60 and 61, Rge. 3), potential reservoir strata are associated with a large-scale, distributary channel-fill complex. The most significant hydrocarbon accumulations are located where thick channel-fill sandstones are located in structurally elevated areas. Since these areas are structurally elevated, the reservoir sandstones are devoid of an associated bottom water zone. Trapping within the channel-fills results from the lateral transition from porous and permeable distributary channel-fill sandstones to impermeable bay-fill mudstones and low porosity, low permeability channel-fill sandstones (Fig. 5.20b).

GR_5 lithosome

The GR_5 lithosome is characterized by a number of small-scale coarsening-upwards bay-fill successions. Within the central portion of the study area, a predominantly east-west trending distributary channel complex has deeply incised into the coarsening-upwards bay-fill successions. These channel-fill sandstones represent the majority of the potential reservoir strata in the GR_5 lithosome. Locally, these distributary channel deposits may attain thicknesses in excess of 20 meters. In the eastern portion of the study area immediately adjacent to the distributary channel-fill complex, a number of bay-fill sandstones are vertically stacked, resulting in a thick, but discontinuous, column of bitumen-saturated sandstone. These bay-fill sandstones have good porosity and permeability characteristics, however, their lateral continuity is highly speculative and thus they may only provide locally acceptable reservoir strata.

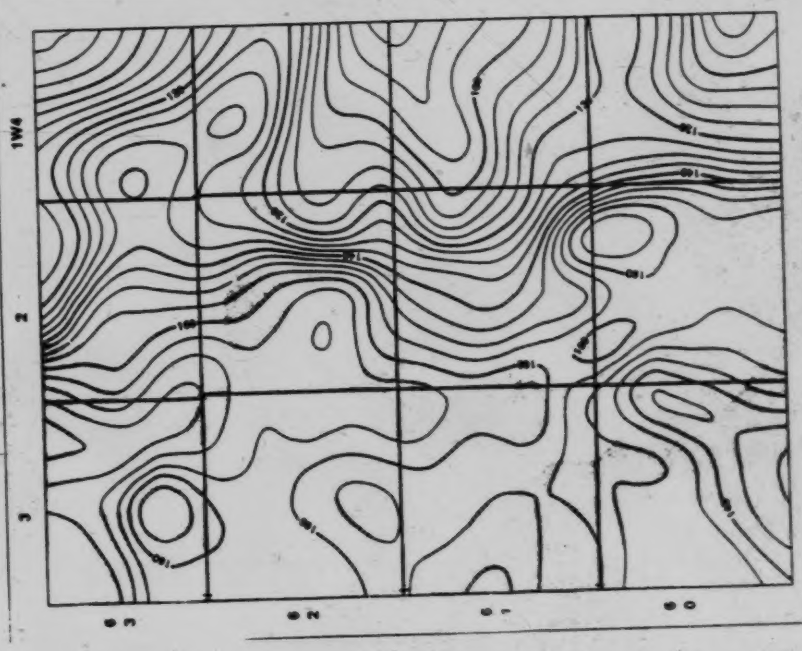
Figure 5.21 illustrates the distribution of hydrocarbons within the GR_5 lithosome. Based on volumetric reserve calculations, the GR_5 lithosome is estimated to contain 257 x 10^6 m^3 of possible oil-in-place.The pattern of hydrocarbon distribution displayed within the GR_5 lithosome is considerably different than that observed in underlying lithosomes.

Figure 5.20

Structural and geological controls on hydrocarbon distribution within the GR_4 lithosome

a) Outline of potential hydocarbon pools in the GR_4 lithosome superimposed on structural contours on the top of the Clearwater Formation. The shaded pattern outlines areas where the thickness of bitumen saturated sandstone exceeds 5 meters and the relative bitumen saturation exceeds 8 weight percent.

b) Net sandstone map GR_4 lithosome.

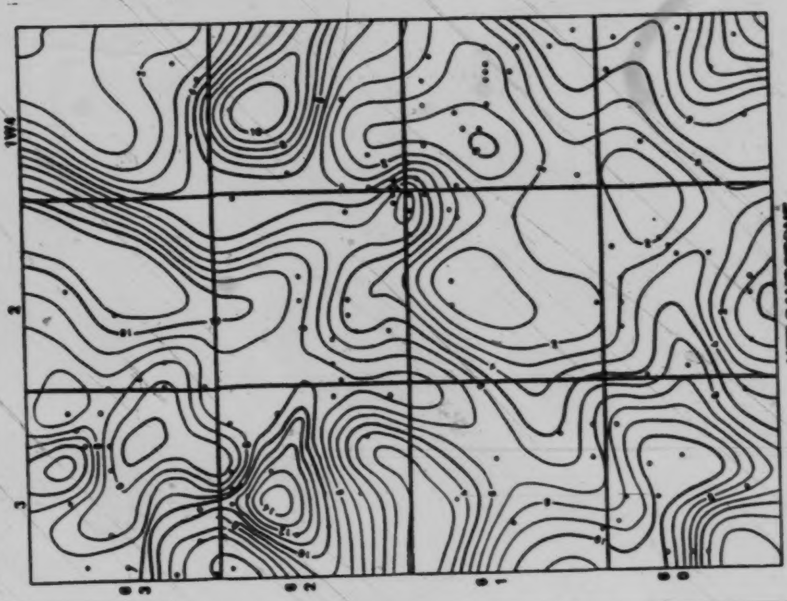


BITUMEN SATURATED SANDSTONE

DISTRIBUTION MAP

GR$_4$ LITHOSOME

A



NET SANDSTONE

GR$_4$ LITHOSOME

1 METER CONTOUR INTERVAL

B

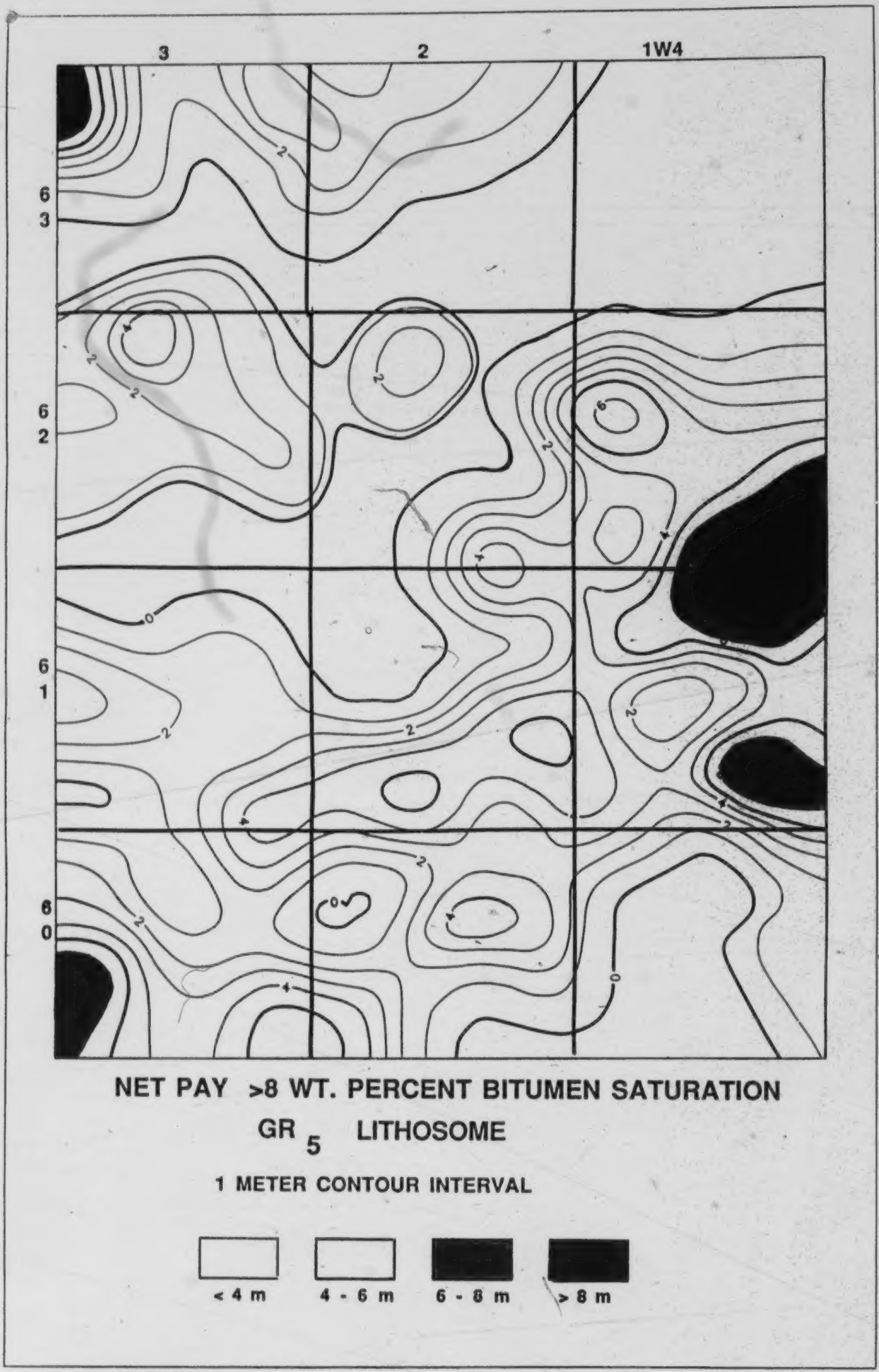


Figure 5.21 Net pay GR_5 lithosome.

Reservoir quality bitumen-saturated sandstones are, for the most part, restricted to the extreme eastern portion of the study area. This is the structurally lowest region of the study area, implying that structural elevation was not a primary factor influencing the distribution of hydrocarbons in the GR_5 lithosome. Rather, stratigraphic or geologic factors appear to govern hydrocarbon distribution. In particular, the distribution of hydrocarbons are directly related to the availability of porous and permeable sandstone. In the GR_5 lithosome, porous sandstone is restricted to the eastern portion of the distributary channel complex and the crevasse splays which developed immediately adjacent to the distributary channel complex. Updip the distributary channel-fill complex becomes mudstone-dominated. This updip transition to muddy channel-fill material effectively traps hydrocarbons in the structurally low-lying areas in the vicinity of the salt solution trough (Fig 5.22). Thus, the availability of porous and permeable sandstone directly influences hydrocarbon distribution, such that it overprints structural trends.

GR_6 Lithosome

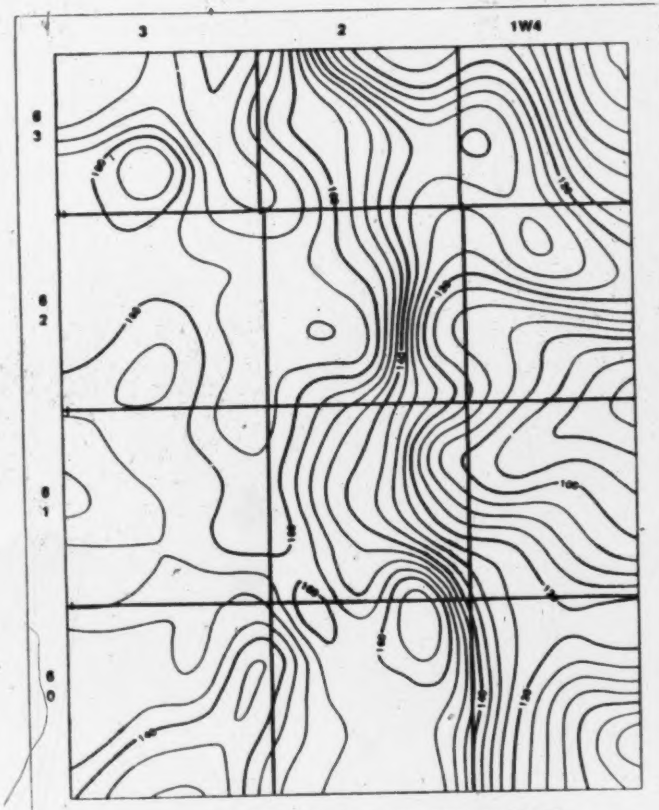
The pattern of sedimentation displayed within the GR_6 lithosome is very similar to that observed within the GR_5 lithosome. Based on volumetric reserve calculations, the GR_6 lithosome is estimated to contain 760×10^6 m^3 of possible oil-in-place.The GR_6 lithosome is characterized by cyclical bay-fill deposits and small-scale and large-scale distributary channel-fill deposits. Crevasse splay sandstones, which form the upper portions of the coarsening-upwards bay-fill successions, are not well-developed in the GR_6 lithosome. The large-scale distributary channel-fill sandstones represent the only viable reservoir strata developed within the study area. A large-scale (25 to 40m thick) distributary channel-fill complex trends east-west across the study area following a trend very similar to that observed within the GR_5 lithosome. The majority of the potential reservoir strata mapped in the GR_6 lithosome are associated with this distributary channel-fill complex (Fig. 5.23). This suggests that the distribution of bitumen-saturated sandstone is directly related to the availability of porous and permeable sandstones. Structural influence appears to be minimal because the channel-fill sandstones which occupy the structurally lowest regions of

Figure 5.22

Structural and geological controls on hydrocarbon distribution within the GR_5 lithosome

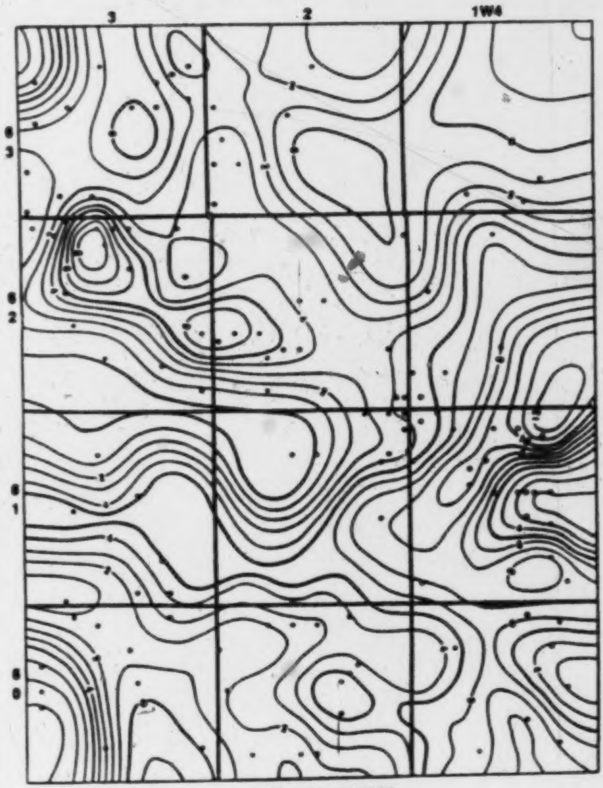
a) Outline of potential hydocarbon pools in the GR_5 lithosome superimposed on structural contours on the top of the Clearwater Formation. The shaded pattern outlines areas where the thickness of bitumen saturated sandstone exceeds 5 meters and the relative bitumen saturation exceeds 8 weight percent.

b) Net sandstone map GR_5 lithosome.



BITUMEN SATURATED SANDSTONE
DISTRIBUTION MAP
GR$_5$ LITHOSOME

A



NET SANDSTONE
GR$_5$ LITHOSOME
METER CONTOUR INTERVAL

B

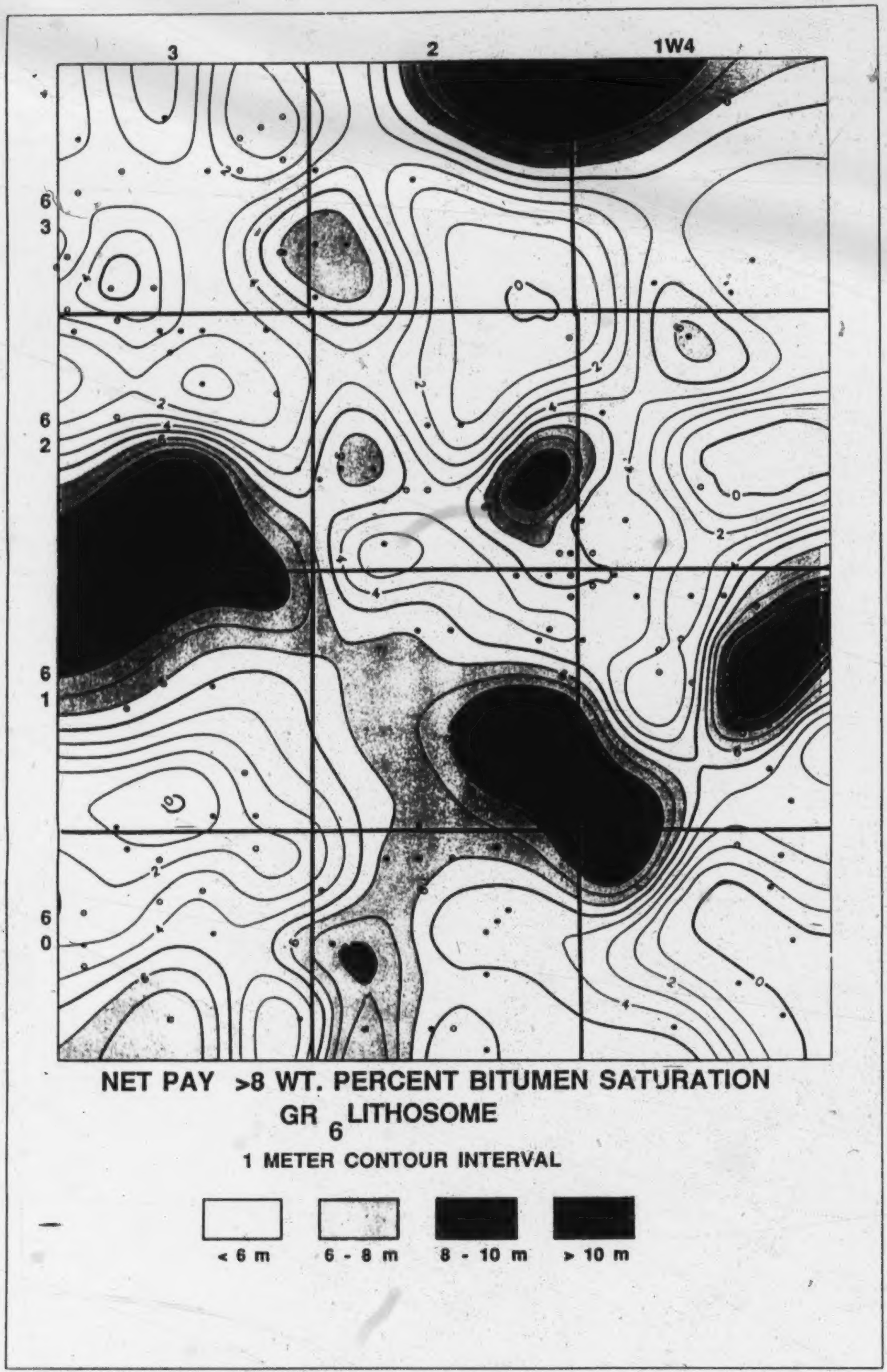


Figure 5.23 Net pay GR_6 lithosome.

the study area are characterized by thick columns of bitumen-saturated sandstone (Fig. 5.24). There does, however, appear to be some structural influence as these sandstones situated in structurally low-lying areas also possess thick bottom water zones below the bitumen-saturated column. Typically sandstones in the structurally lowest areas possess the thickest water columns while sandstones located on or near the ridge are essentially water free.

Within the study area, significant quantities of gas are trapped within the GR_6 lithosome (Fig. 5.25). As previously mentioned, production from the Grand Rapids Formation has primarily been restricted to the recovery of gas from the GR_6 lithosome. A total of 66 gas wells have been completed within this interval, 33 of which are currently producing (20 suspended, 10 abandoned). The ERCB recognizes six distinct gas pools within the boundaries of the study area: Angling, Beaver Crossing, Charlotte Lake, Cold Lake, Kent and Pritchard which produce from the GR_6 lithosome (ERCB designated Colony or Upper Grand Rapids). Volumetric calculations suggest that there is 2356 x 10^6 m^3 of recoverable gas within the boundaries of the study area. To date, 1469 x 10^6 m^3 of gas has been recovered from the GR_6 lithosome, leaving 887 x 10^6 m^3 of remaining recoverable gas within the study area.

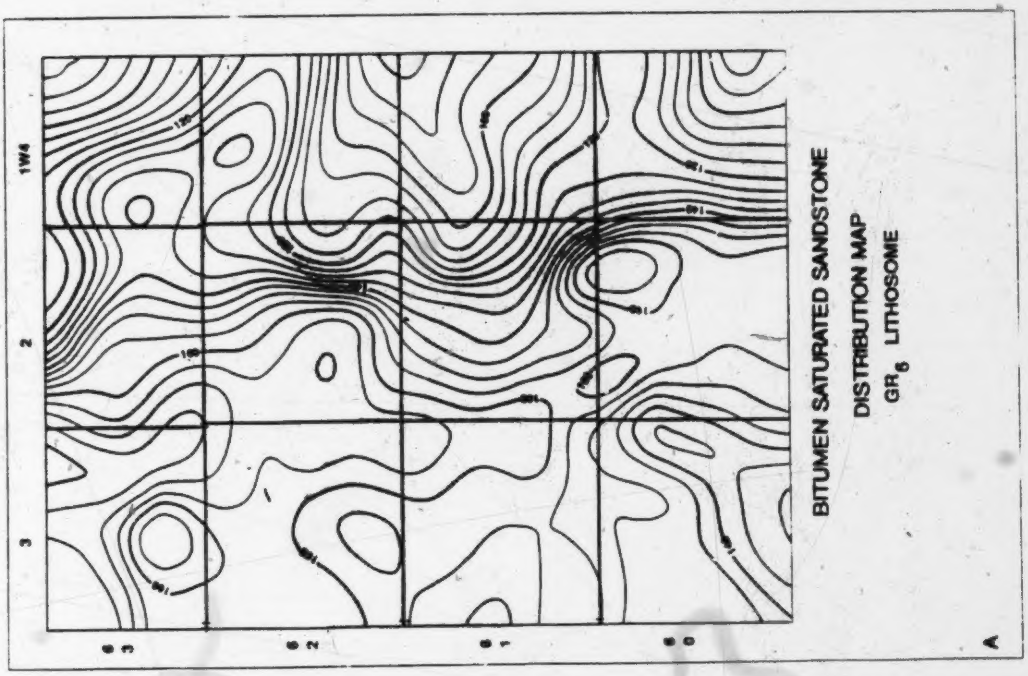
The distribution of gas appears to be directly influenced by present structural attitude. Gas accumulations are typically associated with the structurally highest portions of the study area. The most significant accumulations are found in structural culminations along the eastern margin of the ridge. Typically gas is found overlying bitumen-saturated sandstones as a gas cap. Locally, an upper gas-saturated, lower permeability and lower porosity sandstone may overlie a more permeable bitumen-saturated sandstone. In such cases, the presence of gas overlying bitumen may reflect a decrease in the quality (porosity and permeability) of the reservoir strata.

Figure 5.24

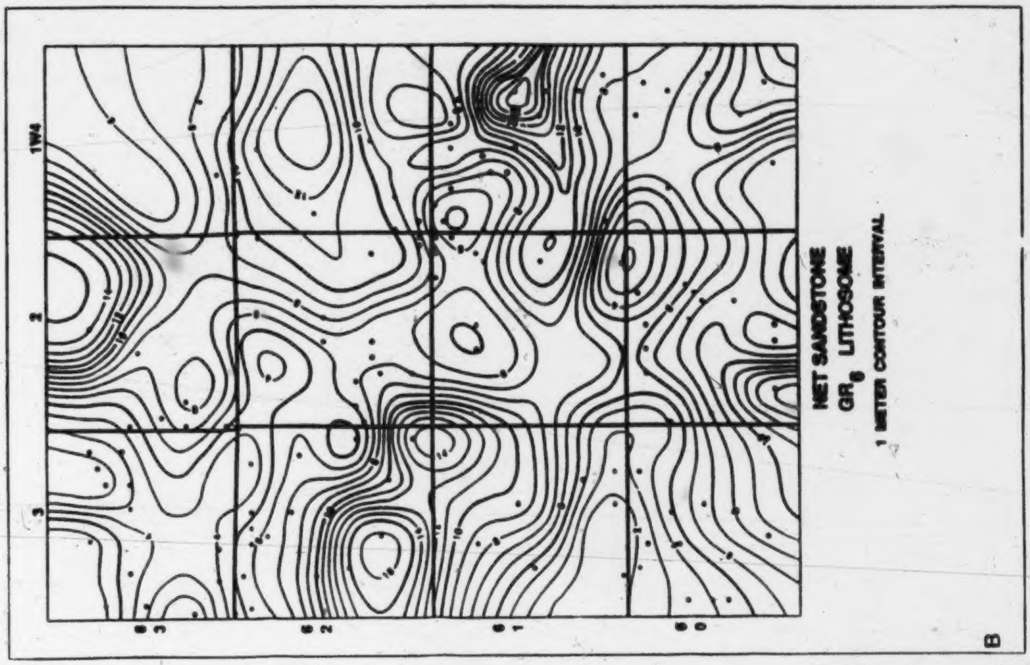
Structural and geological controls on hydrocarbon distribution within the GR_6 lithosome

a) Outline of potential hydocarbon pools in the GR_6 lithosome superimposed on structural contours on the top of the Clearwater Formation. The shaded pattern outlines areas where the thickness of bitumen saturated sandstone exceeds 5 meters and the relative bitumen saturation exceeds 8 weight percent.

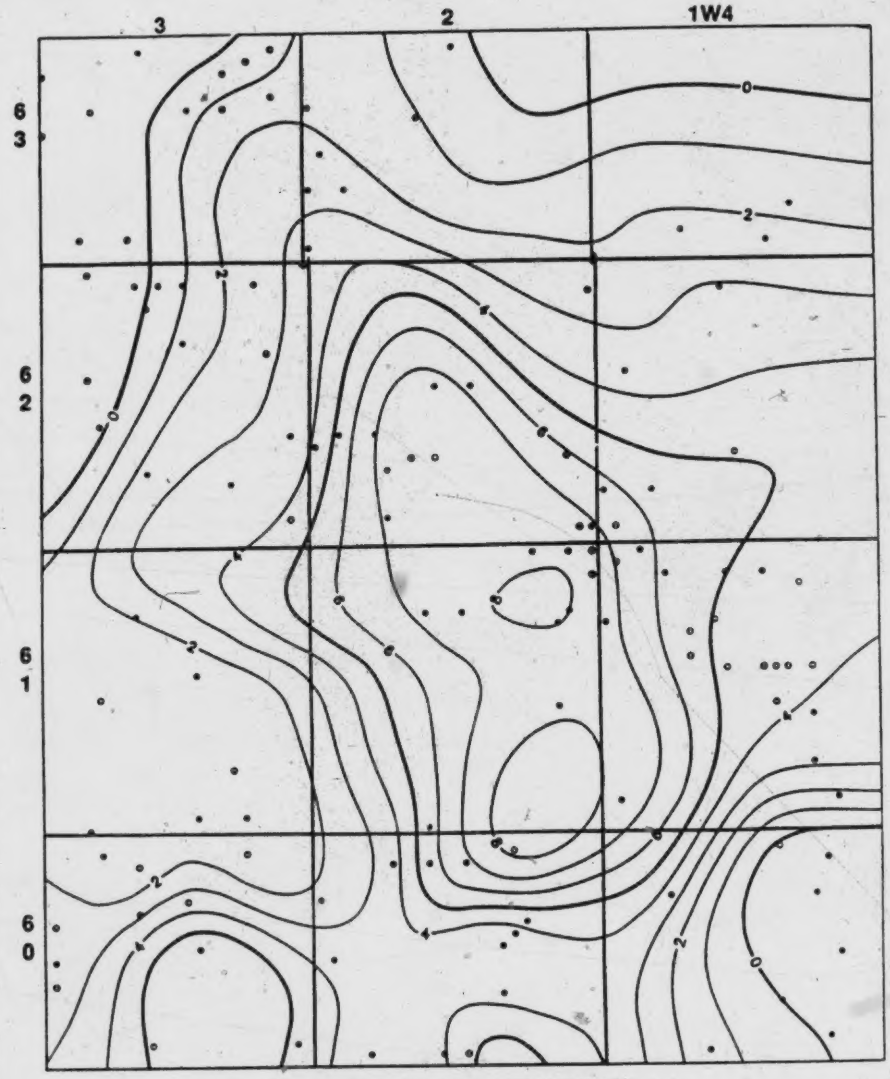
b) Net sandstone map GR_6 lithosome.



BITUMEN SATURATED SANDSTONE
DISTRIBUTION MAP
GR_6 LITHOSOME



NET SANDSTONE
GR_6 LITHOSOME
1 METER CONTOUR INTERVAL



NET PAY GAS GR$_6$ LITHOSOME
1 METER CONTOUR INTERVAL

Figure 5.25 Net gas pay GR$_6$ lithosome.

5.2.4 Geologic Controls on Hydrocarbon Distribution

The four recurring facies associations introduced in Chapter 4 represent the deposits of four distinct, though genetically related, depositional environments. The sand bodies produced within these depositional settings, because of the different processes operating in these settings, are characterized by different reservoir properties.

The shoreface sandstones are restricted to the basal portions of the GR_1 lithosome. These potential reservoir sandstones are typically thick (10-21 m) and display good lateral and vertical continuity. Due to the coarse grain size and the low concentrations of argillaceous material, these sandstones are typically characterized by the highest porosity and permeability values. Average porosity and permeability values for the bitumen-saturated shoreface sandstones are 35 % and 4700 mD respectively. The shoreface sandstones are typically characterized by a thick bottom water zone which is overlain by a transitional zone and a thin bitumen-saturated column. Typically the permeability, and subsequently the weight percent bitumen saturation values, are significantly reduced in the water-saturated sandstones due to the development of authigenic clays and cements (siderite, sericite, montmorillonite, kaolinite, calcite, quartz, *etc.*); diagenetic developments which are inhibited in the bitumen-saturated sandstones (*cf.* Kramers, 1974; Orr *et al.*, 1977).

The delta front sandstones, because of the relatively high energy depositional setting, exhibit similar reservoir properties to the shoreface sandstones. The delta front sandstones display excellent lateral and vertical continuity as to be expected in wave-dominated systems. However, the delta front sandstones are typically fine-grained and contain a higher relative proportion of argillaceous material. This serves to effectively reduce the porosity and permeability of the sandstones. Average porosity and weight percent bitumen saturation values for the delta front sandstones are 32 % and 8.6 % respectively. The thickness of the delta front sandstones (4 to 8 m) significantly reduces the attractiveness of this sandstone type. However, the relatively homogeneous porosity and permeability of the delta front sandstones and the absence of bottom water zones does make the delta front sandstones ammenable to enhanced oil recovery schemes.

The crevasse splay and crevasse channel sandstones, which comprise the upper portions of many bay-fill successions, do not have any significant reservoir potential. Many crevasse splay sandstones display similar reservoir properties to the delta front sandstones. Typical porosity and weight percent bitumen saturation values for the crevasse splay sandstones are 32 % and 8.2 % respectively. However, the crevasse splay sandstones are typically thin (1 to 2 m), discontinous and contain appreciable amounts of argillaceous material which significantly reduces the possible reserves associated with this sandstone type. The heterogeneous internal nature of these sandstone bodies reflects the complex nature of the depositional environment.

In the preceding discussions it was illustrated that a significant volume of hydrocarbons are associated with the distributary channel-fill sandstones, particularly within the GR_4 and GR_6 lithosomes. Individual distributary channel-fill sandstones average 8 to 15 meters in thickness. Superposition of several events of channel-fill deposition produced multistorey sandstone bodies which may be up to 40 meters thick. Furthermore, the stacking of channel-fill successions from a number of lithosomes may produce an exceptionally thick bitumen-saturated sandstone column. The coarser grain size of the channel-fill sandstones results in excellent porosity and permeability characteristics. Average porosity and weight percent bitumen saturation values for the distributary channel-fill sandstones are 35 % and 10.6 % respectively. However, the reservoir quality of the channel-fill sandstones is reduced by the abundant and unpredictable transitions to non-porous channel -fill material. The heterogeneous nature of the distributary channel-fill sandstones reflects the variability of processes active within this depositional setting. Furthermore, many of the distributary channel-fill sandstones are characterized by thick bottom water zones, particularly in the eastern portion of the study area. Despite this, the distributary channel-fill deposits, especially those which occur in the GR_6 lithosome, volumetrically appear to be the most attractive exploitation and development targets due to the potential thickness of the bitumen-saturated sandstone column that can be developed. However, their inherent internal heterogeneity and their narrow linear geometry effectively increases risk and reduces the attractiveness of this sandstone type.

5.2.5 Trapping Mechanisms

Trapping of hydrocarbons within the Grand Rapids Formation, particularly within the GR_1, GR_2, GR_3 and GR_4 lithosomes, appears to be primarily related to the present structural attitude of the reservoir strata within the study area. The present structural attitude of the Mannville Group strata is, for the most part, a result of post-Second White Speckled Shale solution of the Middle Devonian Prairie Evaporite Formation. The predominant structural feature within the study area is a north-south trending ridge which parallels the salt solution trough. A large proportion of the hydrocarbons contained within the reservoir units of the Grand Rapids Formation are situated on structurally high areas of the ridge and trapped in associated structural culminations along the ridge (Figs. 5.26, 5.27 and 5.28).

Stratigraphic traps and combined structural-stratigraphic structures are locally significant in the distribution of hydrocarbons. Many of the large-scale distributary channel-fill complexes host significant volumes of hydrocarbons (*i.e.* GR_5 and GR_6 lithosomes). In such settings, because the distributary channel-fill sandstones represent the only available porous and permeable material they may contain hydrocarbons despite occupying an unfavourable structural position. The thickness of the hydrocarbon column developed is partially influenced by structure (Figs. 5.26, 5.27 and 5.28). In low-lying areas, the channel-fill sandstones may possess a thick bottom water column, whereas in structurally elevated areas, the thickness of the bottom water column is significantly reduced..

5.2.5 Hydrocarbon migration and entrapment

The relationship between structure and hydrocarbon distribution as depicted by the suite of hydrocarbon distribution maps has significant implications concerning the timing of

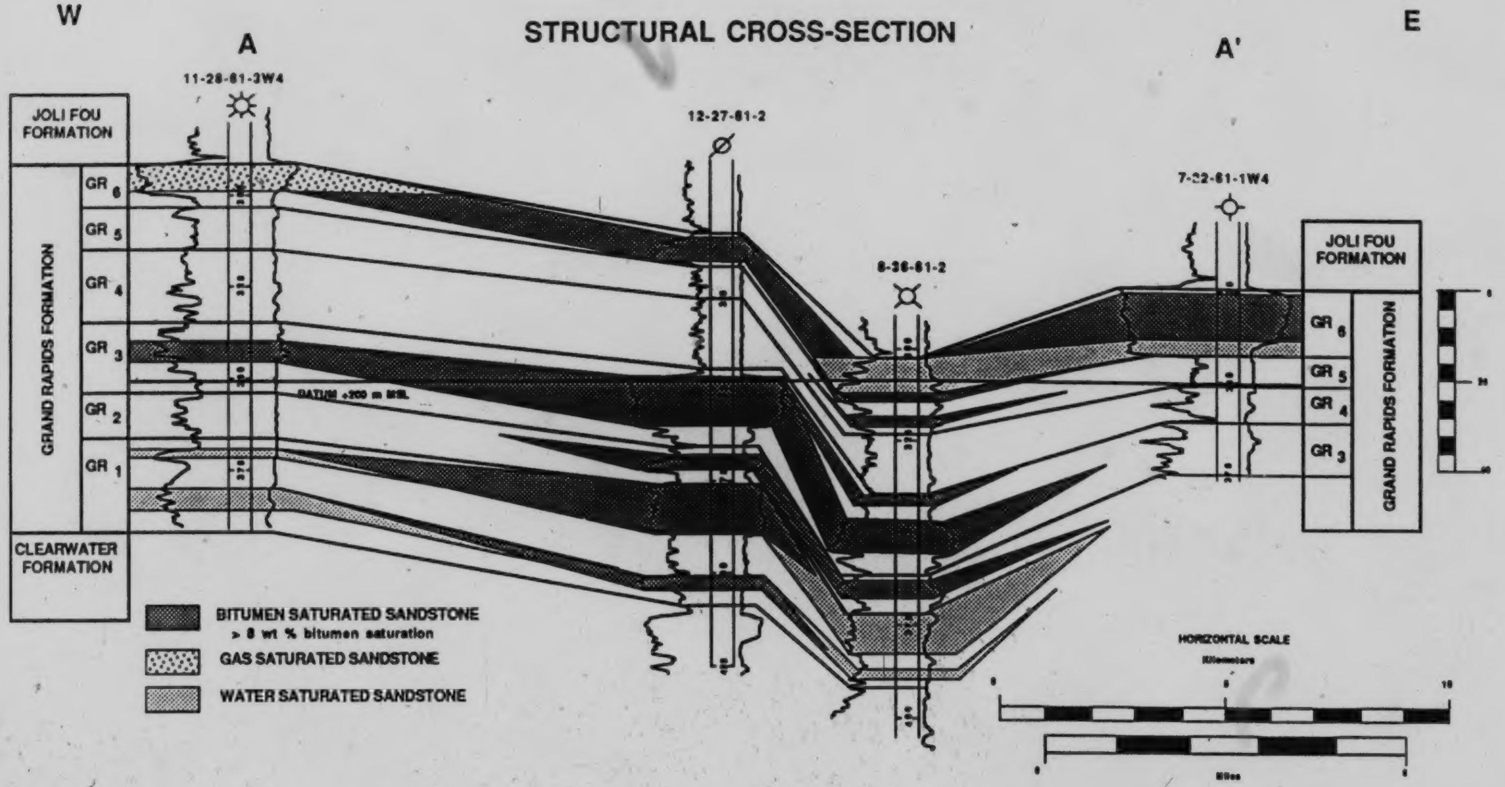


Figure 5.26 Structural cross-section A - A' illustrating the distribution of hydrocarbons.

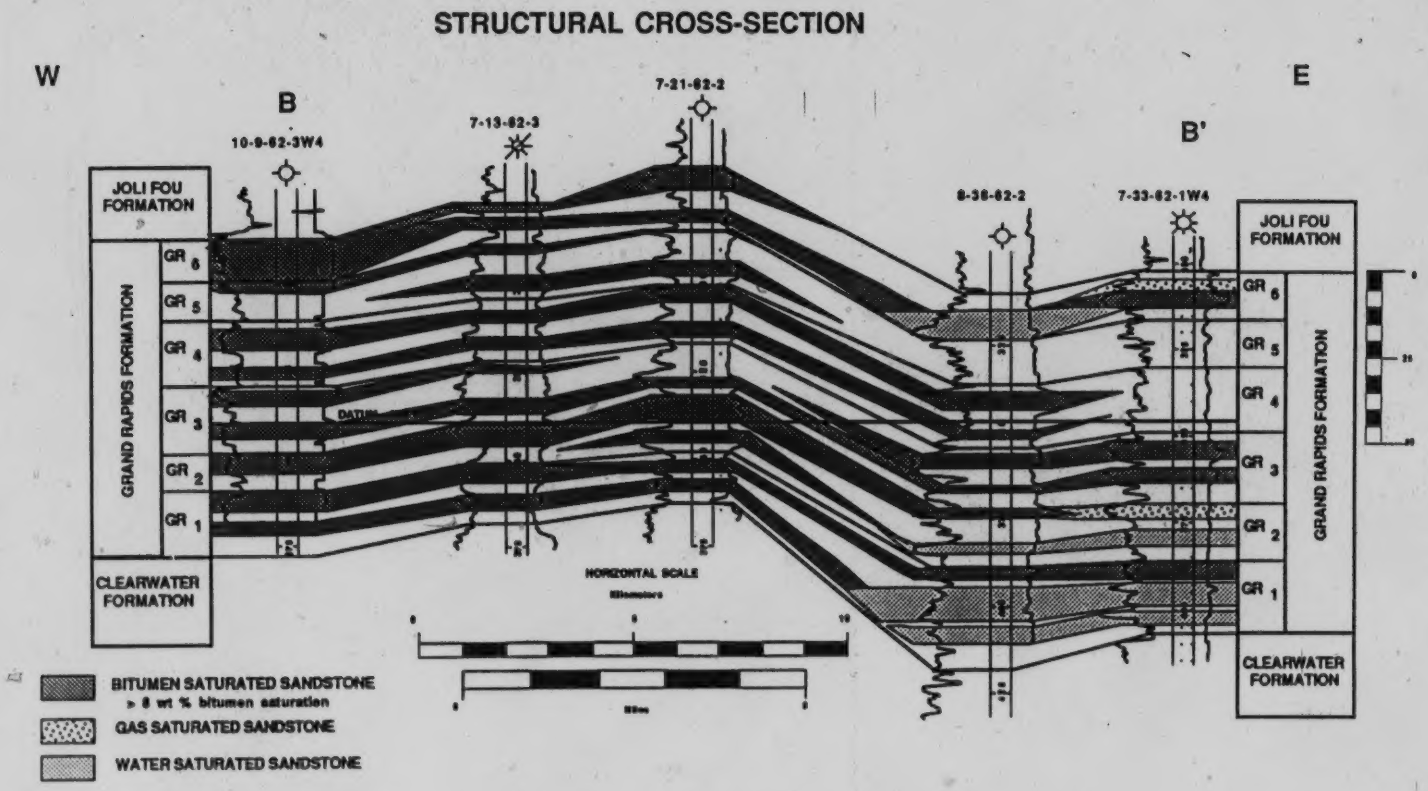


Figure 5.27 Structural cross-section B - B' illustrating the distribution of hydrocarbons.

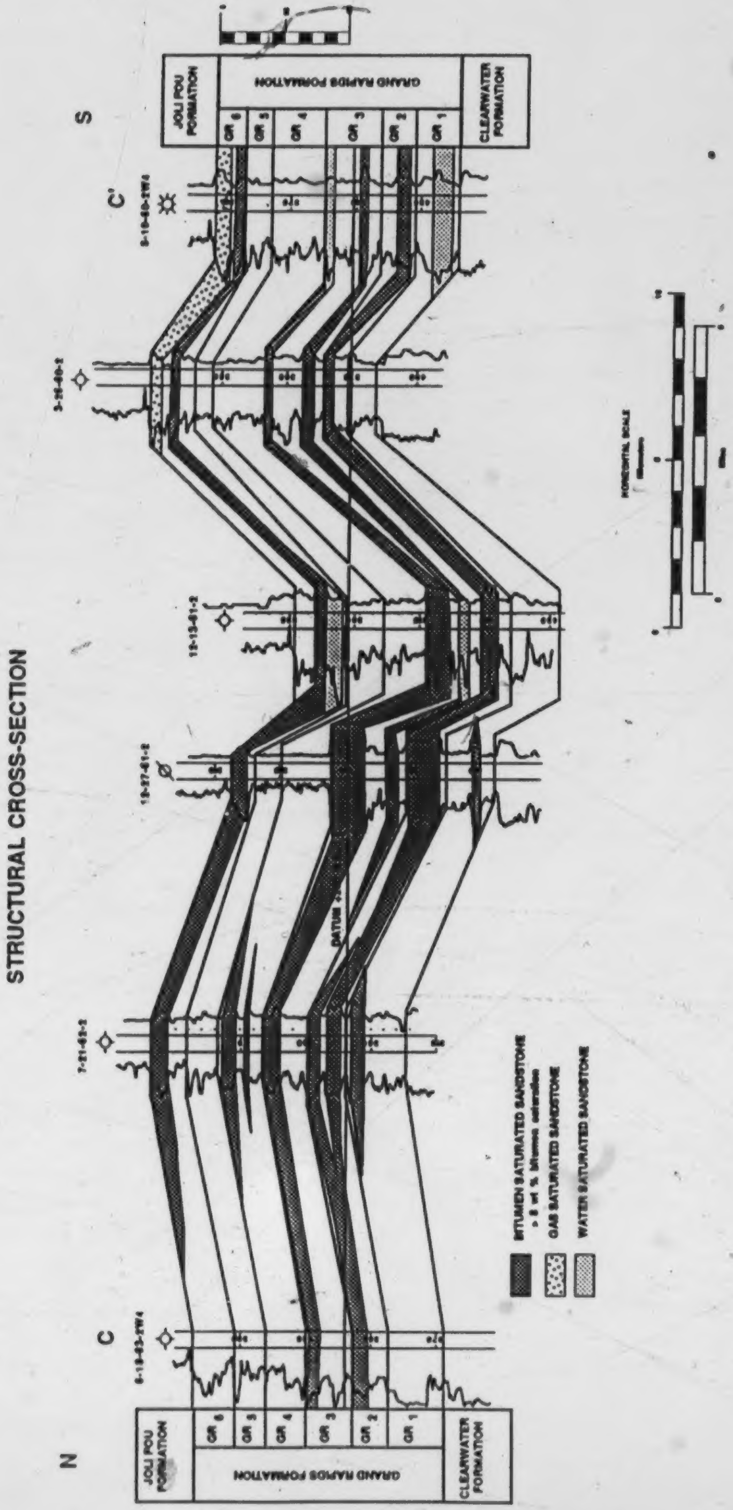


Figure 5.28 Structural cross-section C - C' illustrating the distribution of hydrocarbons.

hydrocarbon emplacement. From the data presented two possible interpretations exist: (1) hydrocarbons were emplaced contemporaneous with or soon after the deformation event which produced the present structural attitude of the Grand Rapids Formation strata (post-Second White Speckled Shale); or (2) hydrocarbons were emplaced contemporaneous with or sometime after Mannville Group deposition, but prior to the deformation event responsible for the present structural configuration. The coincidence of structural contours of the oil-water contact and net pay isopachs with the trend of structural contours suggest that oil migration and emplacement preceded the development of the present-day structure. Buoyancy and gravity segration laws dictate that the interface between hydrocarbons and water must be horizontal at the time of implacement. If the reservoir is disturbed by a subsequent structural deformation event, the hydrocarbons will readjust to maintain horizontal interfaces, provided the permeability of the reservoir rock permits this readjustment (Wilson, 1990). Thus, the parallelism of hydrocarbon-water interfaces and structural contours indicates that, for the most part, hydrocarbons were able to adjust to new structural attitudes created by post-Second White Speckled Shale solution-related subsidence.

However, there are areas within the study area where hydrocarbons have readjusted their positioning in response to post-accumulation deformation. Significant quantities of hydrocarbons are found trapped within distributary channel-fill sandstone despite occupying structurally low-lying areas. Here hydrocarbons had migrated and were trapped within the distributary channel-fill sandstones prior to the deformational event(s) which produced the present structural configuration. The lateral, vertical and updip facies transitions to non-permeable carbonaceous mudstones effectively trapped the hydrocarbons within the distributary channel-fill sandstones. Thus hydrocarbons were effectively trapped within these sandstones despite their present day unfavourable structural positions. Inclined and irregular oil-water contacts also suggest that oil migration preceded the development of present-day structure, but, the hydrocarbons were not able readjust. Due to progressive cementation and plugging of porosity by diagenesis in water-saturated reservoir rock, hydrocarbons cannot readjust at the water interface.Similarly, the presence of a basal "tar mat" or a diagenetic permeability barrier may effectively seal an oil accumulation at the oil water contact (Wilson, 1990). In either case, it is possible to constrain the time of hydrocarbon emplacement, since sealing must post-date emplacement and since the timing of deformation has been ascertained from the preceding discussion Thus, it appears that the hydrocarbons trapped within the Grand Rapids Formation are a result of early, immature oil generation from proximal sources which were trapped soon after deposition of the Grand Rapids Formation, in structures present at that time, and then subsequently redistributed in response to a later structural deformation event; specifically, post-Second White Speckled Shale solution-related subsidence.

5.2.6 Conclusions and Implications for Development of the Grand Rapids Formation

The preceding discussions outlined the geologic, stratigraphic and structural controls on hydrocarbon distribution. From these discussions, it is clear that the Grand Rapids Formation consists of a number of multiple, stacked reservoirs. The distribution of hydrocarbons is related to the availability of porous and permeable sandstone and structural elevation. Given that porous and permeable sandstone is available, the quantity of bitumen-saturated sandstone is primarily related to the structural attitude of the reservoir sandstone. Structure within the study area is mainly related to post-depositional solution of the Prairie Evaporite Formation. Reservoir quality and geometry is directly related to depositional processes.

Both structural and stratigraphic trapping styles are significant within the vicinity of the study area. However the vertical stacking of distinct, bitumen-saturated sandstone bodies which have similar, if not identical, structural attitudes but differing depositional histories suggests that structure exerts the predominant influence on hydrocarbon distribution. This predominance of structural influence on the distribution of hydrocarbons has important implications which should be considered for the future development of the Grand Rapids Formation and the Cold Lake oil sands area as a whole. The majority of the hydrocarbons within the study area are structurally trapped on or along a narrow ridge created by the superposition of the salt solution trough upon the regional dip of the Western Canadian Sedimentary Basin.

CHAPTER 6 SUMMARY AND CONCLUSIONS

The Lower Cretaceous Grand Rapids Formation, within the Cold Lake oil sands area consists of a complex succession of shoal-water deltaic and marginal marine deposits. Six-flooding surface-bounded lithosomes record six, distinct intervals of delta complex construction and abandonment.Overall these six lithosomes are arranged into a progradational stacking pattern reflecting the continual basinward shift in the locus of active shoreline sedimentation throughout the deposition of the Grand Rapids Formation. Relatively slow, continuous subsidence facilitated the stacking of mutliple regressive deltaic sandstone bodies.

The most characteristic feature of the Grand Rapids Formation is the vertical repetition of facies and depositional environments. Autocyclic processes, specifically repeated cycles of delta lobe progradation, avulsion, channel switching and lobe abandonment, can explain the lateral and vertical distribution of facies and depositional environments observed within the Grand Rapids Formation. The application of an autocyclic delta model to the Grand Rapids Formation to explain the lateral and vertical facies relationships and cyclical pattern of sedimentation makes it unnecessary to invoke periodic pulses of basinal subsidence, cyclical eustatic sea level fluctuations or cyclical fluctuations in sediment supply.

The Grand Rapids Formation within the Cold Lake oil sands area has vast resource potential. Volumetric reserve calculations suggest that within the study area there is 3, 526 x 10^6 m^3 (22 billion barrels) of oil-in-place. To date only a very small percentage of this figure has been recovered. The distribution of this vast quantity of hydrocarbons within the Grand Rapids Formation is, for the most part, related to primary facies distribution and the present structural elevation of the reservoir quality sandstones. Sandstone geometry and quality are related to the primary depositional and, to a lesser extent, post-depositional processes. These depositional processes directly influenced the distribution of facies and the reservoir properties of the different depositional facies. The recognition of cyclic deltaic sedimentation driven by autocyclic processes inherent within delta systems as the mechanism for deposition of the Grand Rapids Formation significantly increases the predictability of depositional environments and the distribution of reservoir quality sandstone. The quantity or thickness of the bitumen-saturated column that is developed is, in turn, related to the structural attitude or elevation of the reservoir sandstone. Structure, for the most part, is related to structural subsidence associated with solution of the Middle Devonian Prairie Formation. Solution-related subsidence has occurred episodically since deposition of the Prairie Formation. The most significant episode of solution-related subsidence appears to have occurred sometime after deposition of the Second White Speckled Shale. A large percentage of the potential reservoir strata within the study area is associated with a north trending ridge created by solution-related subsidence in a narrow trough which is coincident with the edge of the Middle Devonian Prairie Evaporite Formation. A thorough understanding of the complex, but somewhat predictable, distribution of facies and depositional environments combined with an appreciation of the structural setting and timing of deformation will facilitate the most effective exploitation of the vast resource potential contained within the strata of the Grand Rapids Formation.

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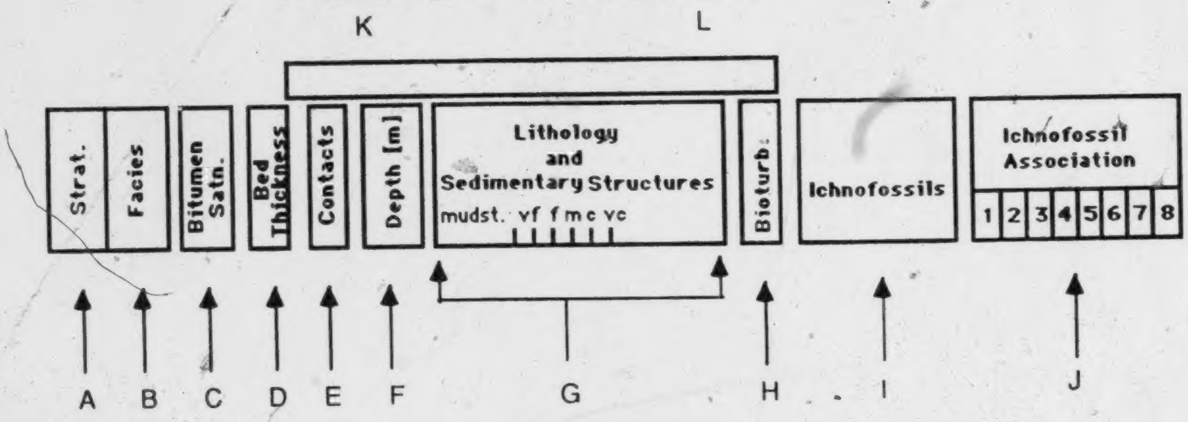
APPENDIX

LEGEND TO [illegible] OMPANY LITHOLOGS



A. Stratigraphic Framework

JF = Joli Fou Formation
GR = Grand Rapids Formation

GR_1
GR_2
GR_3 GENETIC STRATIGRAPHIC SUBDIVISIONS
GR_4
GR_5
GR_6

CLR = Clearwater Formation

B. Facies Scheme

1 Mudstone
1a Dark grey laminated mudstone with abundant mollusc shell fragments
1b Dark to light grey interlaminated mudstone
1c Thinly laminated to massive mudstone
1d Carbonaceous mudstone

2 Bioturbated sandstone
3 Small-scale cross-stratified sandstone
4 Large-scale cross-stratified sandstone
5 Planar-laminated to low-angle cross-stratified sandstone
6 Structureless sandstone

7 Heterolithic facies
7a Interbedded sandstone and mudstone (interbeds < 1 cm.)
7b Interbedded sandstone and mudstone (sandstone interbeds 1-10 cm.)
7c Homogenized sandstone and mudstone

C. Bitumen saturation

0 = non-saturated
1 = low
2 = moderate
3 = high
4 = very high

D. Bed Thickness

1= laminated (<1 cm.)
2= small-scale cross-stratified (1-4 cm.)
3= large-scale cross-stratified (> 4 cm.)

E. Basal contacts

———	Sharp, planar
- - - - -	Gradational
s ———	Scoured
~~	Irregular

F. Lithology and sedimentary structures

■	Mudstone
▨	Siltstone
☰	Heterolithic facies
▨	Sandstone
←C	Coal layer
c	Disseminated carbonaceous debris
-c-	Carbonaceous laminae
ptgs	Mudstone or composite sandstone-mudstone partings
xxx	Indurated zone Fe= siderite Ca= calcite

◡	Trough cross-stratification
///	Planar tabular cross-stratification
═	Parallel lamination
^	Small-scale cross-stratification (ripple cross-lamination)
⋀⋀	Climbing ripple cross-lamination
/15°	Angle of forset inclination
●●	Mudstone intraclasts
⅄	Rootlets
ɣ	Syneresis cracks

Grain size:
Mudst.= < 0.0625 mm.
vf = 0.0625-0.125 mm.
f = 0.125-0.25 mm.
m = 0.25-0.5 mm.
c = 0.5-1.0 mm

G. Bioturbation

0 = no apparent bioturbation
1 = slight bioturbate texture
2 = moderate bioturbation
3 = intense bioturbation

H. Ichnofossils

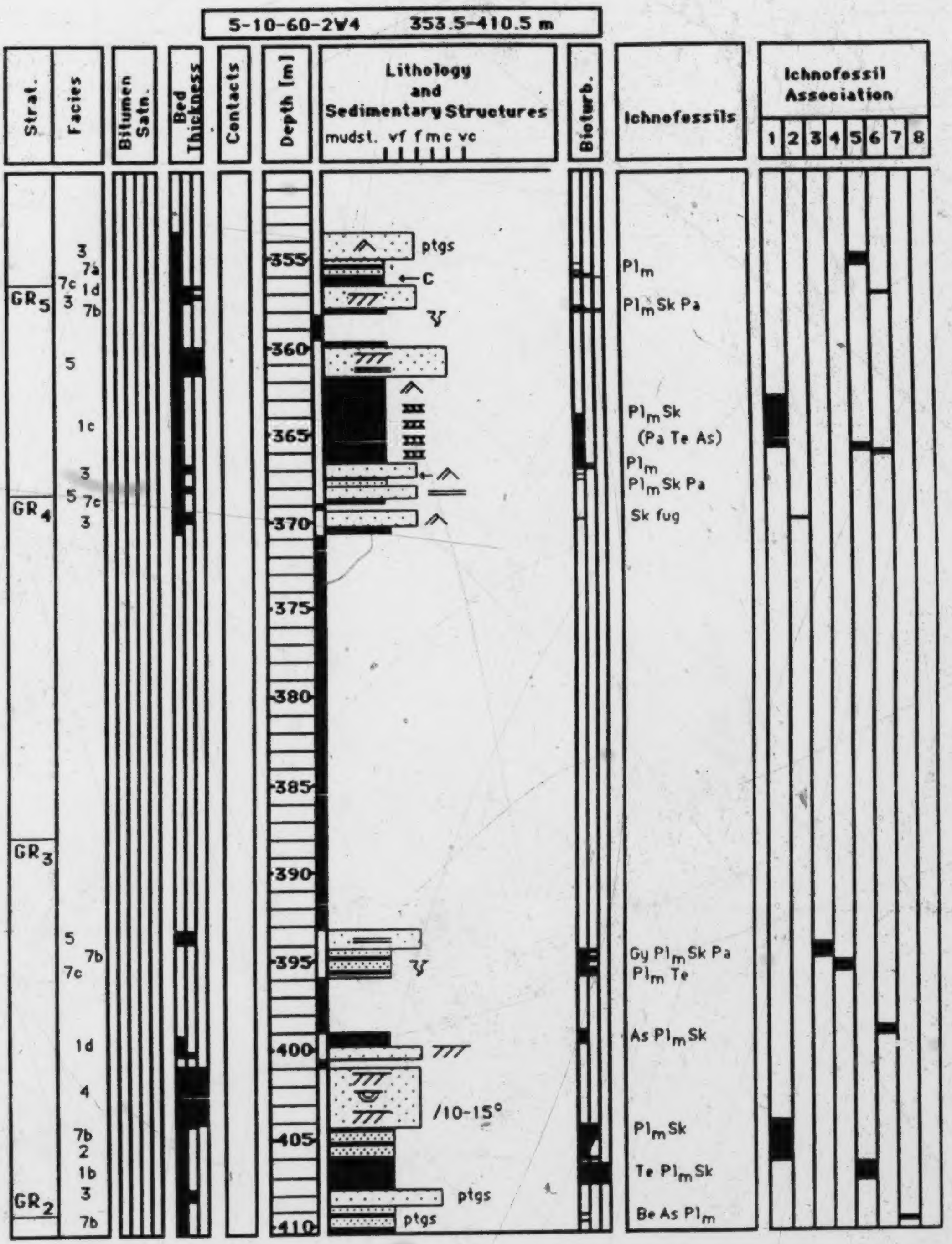
As = *Asterosoma*
Ch = *Chondrites*
Co = *Conichnus*
Cy = *Cylindrichnus*
Gy = *Gyrolithes*
He = *Helminthopsis*
Ma = *Macaronichnus*
Mo = *Monocraterion*
Plm = *Planolites beverlyensis*
Plb = *Planolites montanus*
Pa = *Palaeophycus*
Rh = *Rhizocorrallium*
Ro = *Rosselia*
Sk = *Skolithos*
Te = *Teichichnus*
Zo = *Zoophycos*

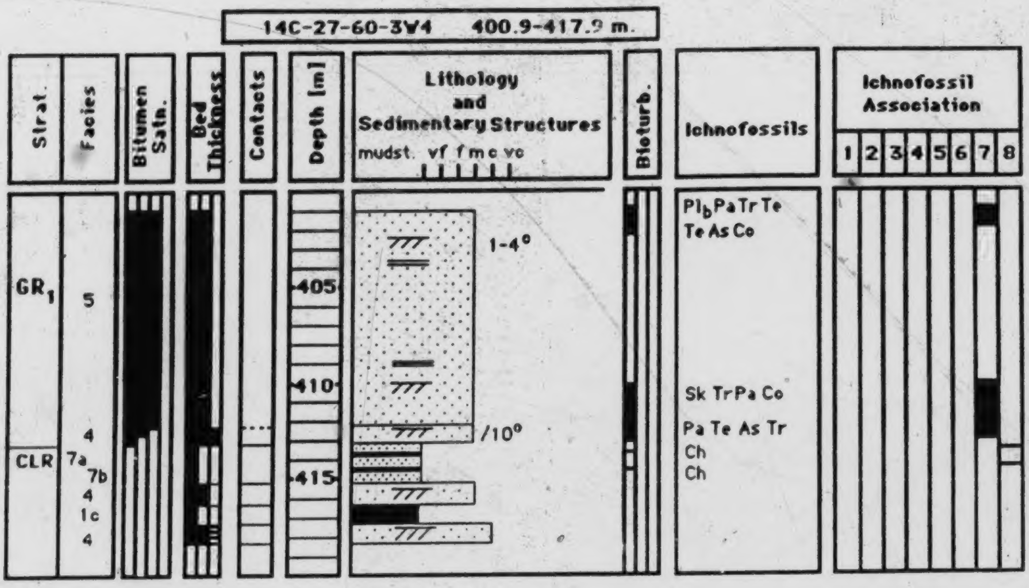
J. Recurring ichnofossil Associations

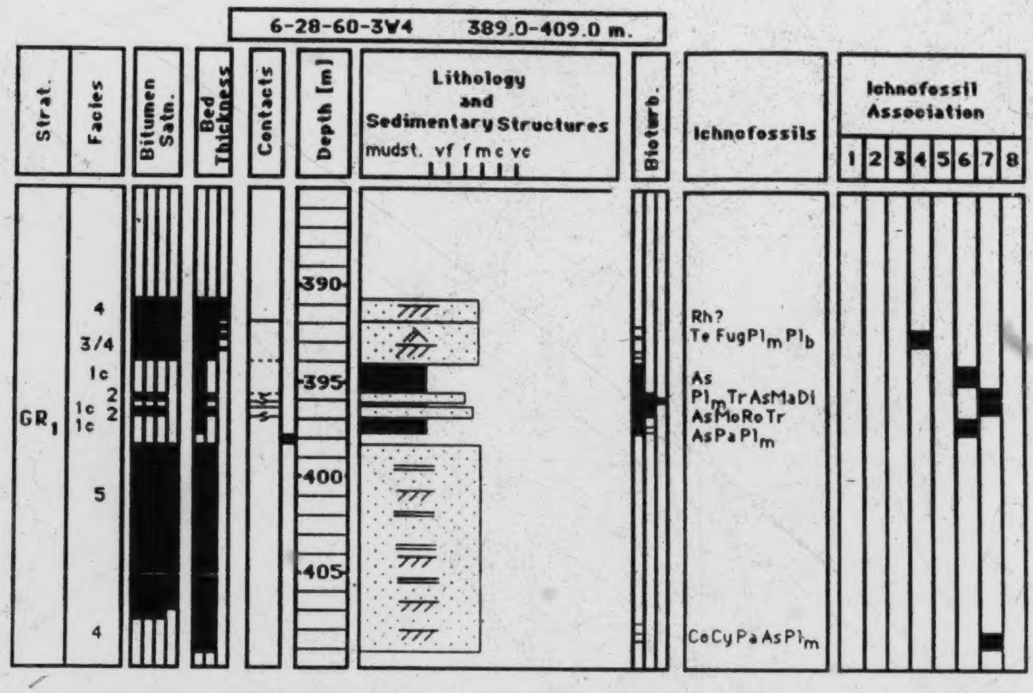
1 = *Skolithos-Planolites*
2 = *Skolithos*
3 = *Gyrolithes*
4 = *Teichichnus*
5 = *Planolites*
6 = *Palaeophycus-Planolites*
7 = *Skolithos-Palaeophycus*
8 = *Zoophycus*

K Well location

L. Cored interval


5-10-60-2W4 353.5-410.5 m
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR5
GR4
GR3
GR2
3
7a
7c
1d
3
7b
5
1c
3
5
7c
3
5
7b
7c
1d
4
7b
2
1b
3
7b
355
360
365
370
375
380
385
390
395
400
405
410
ptgs
C
/10-15°
ptgs
ptgs
Pl$_m$
Pl$_m$ Sk Pa
Pl$_m$ Sk
(Pa Te As)
Pl$_m$
Pl$_m$ Sk Pa
Sk fug
Gy Pl$_m$ Sk Pa
Pl$_m$ Te
As Pl$_m$ Sk
Pl$_m$ Sk
Te Pl$_m$ Sk
Be As Pl$_m$


14C-27-60-3W4 400.9-417.9 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR$_1$
5
4
CLR
7a
7b
4
1c
4
405
410
415
1-4°
/10°
Pl$_b$ Pa Tr Te
Te As Co
Sk Tr Pa Co
Pa Te As Tr
Ch
Ch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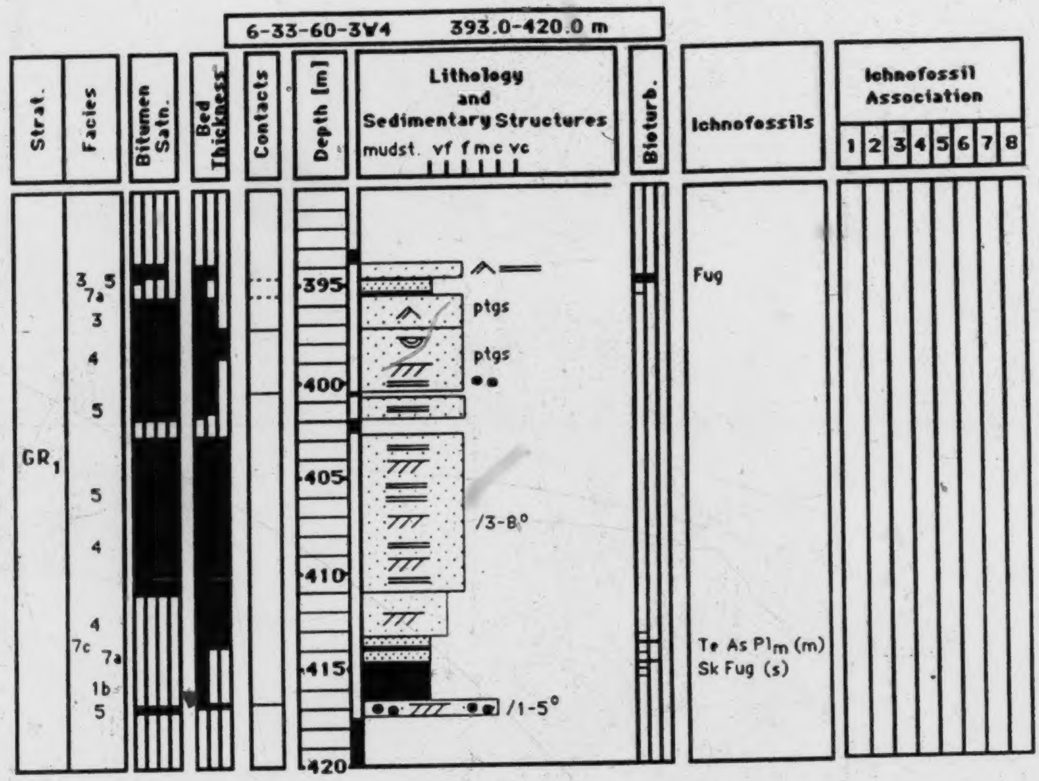
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
390
395
400
405
GR1
4
3/4
1c
2
1c
2
1c
5
4
Rh?
Te FugPlm Plb
As
Plm Tr AsMaDi
AsMoRoTr
AsPaPlm
CoCyPaAsPlm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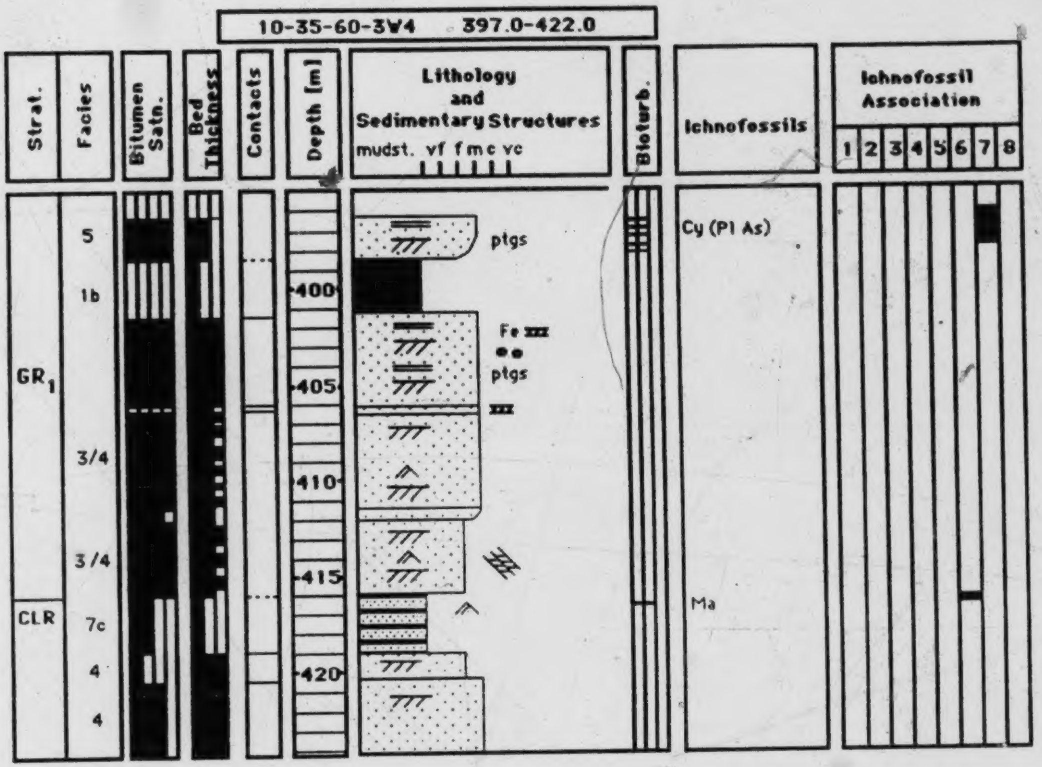
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR1
3 5
7a
3
4
5
5
4
4
7c 7a
1b
5
395
400
405
410
415
420
ptgs
ptgs
/3-8°
/1-5°
Fug
Te As Plm (m)
Sk Fug (s)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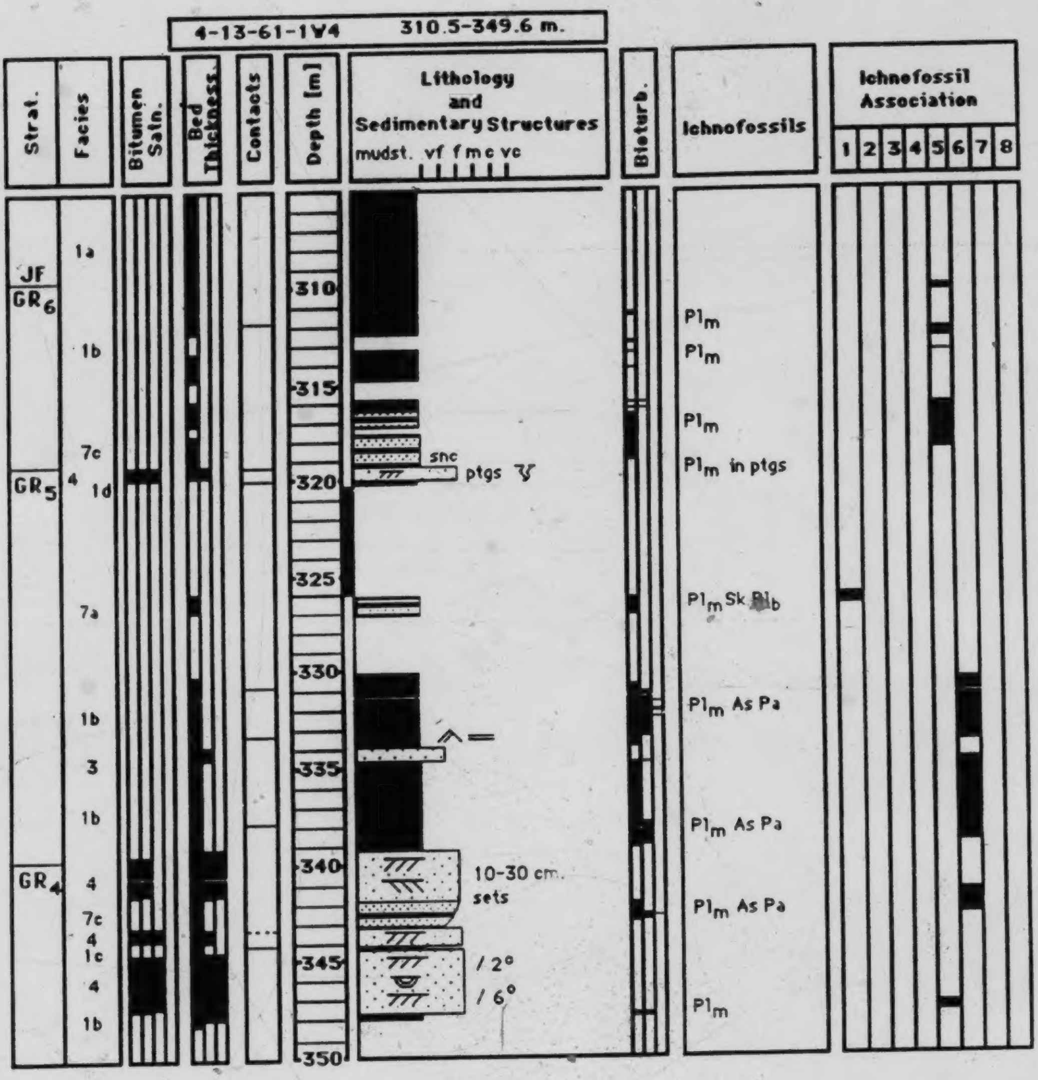
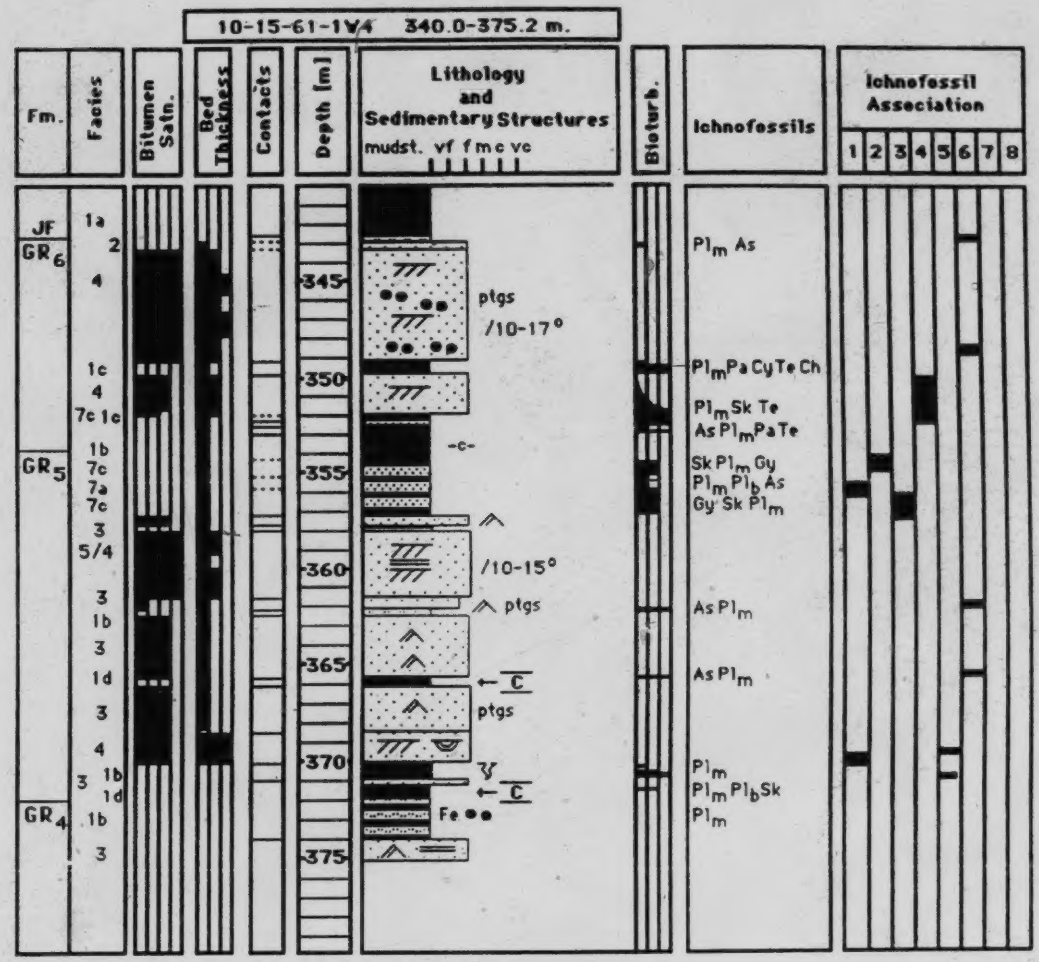
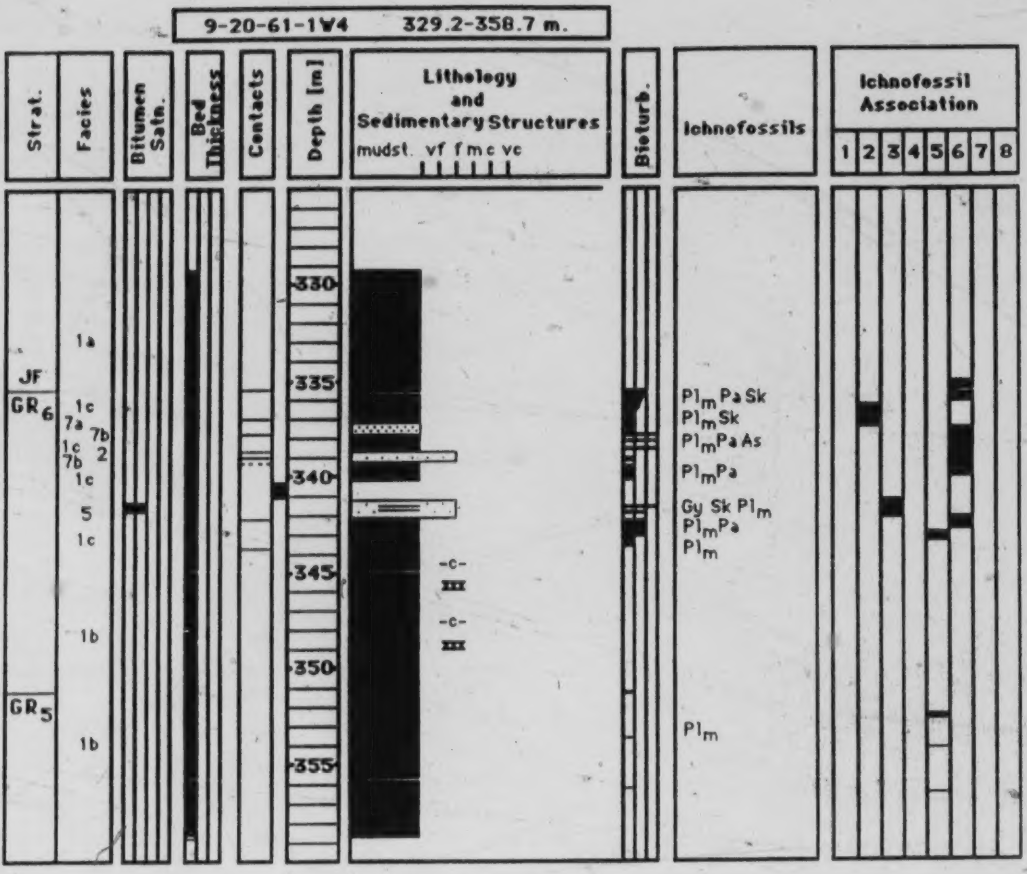
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR1
CLR
5
1b
3/4
3/4
7c
4
4
400
405
410
415
420
ptgs
Fe
ptgs
Cy (Pl As)
Ma


4-13-61-1W4
310.5-349.6 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
JF
GR6
GR5
GR4
1a
1b
7c
4
1d
7a
1b
3
1b
4
7c
4
1c
4
1b
310
315
320
325
330
335
340
345
350
snc
ptgs
10-30 cm. sets
/ 2°
/ 6°
Pl m
Pl m
Pl m
Pl m in ptgs
Pl m Sk Pl b
Pl m As Pa
Pl m As Pa
Pl m As Pa
Pl m


10-15-61-1W4 340.0-375.2 m.
Fm.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
JF
GR6
GR5
GR4
1a
2
4
1c
4
7c 1c
1b
7c
7a
7c
3
5/4
3
1b
3
1d
3
4
3 1b
1d
1b
3
345
350
355
360
365
370
375
ptgs
/10-17°
-c-
/10-15°
ptgs
C
ptgs
C
Fe
Pl m As
Pl m Pa Cy Te Ch
Pl m Sk Te
As Pl m Pa Te
Sk Pl m Gy
Pl m Pl b As
Gy Sk Pl m
As Pl m
As Pl m
Pl m
Pl m Pl b Sk
Pl m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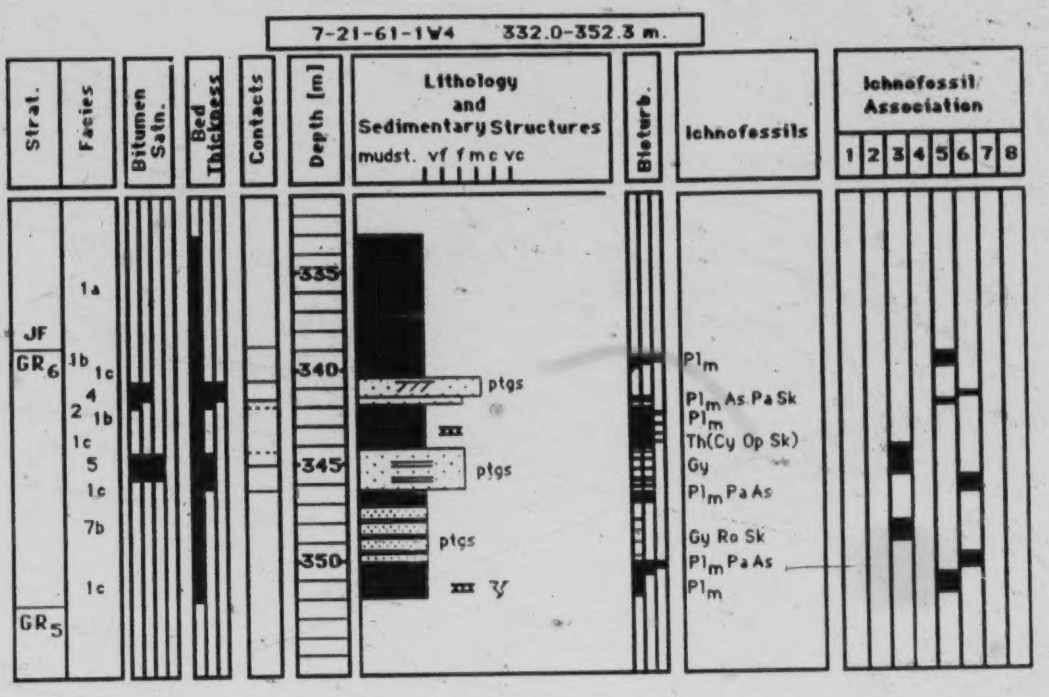
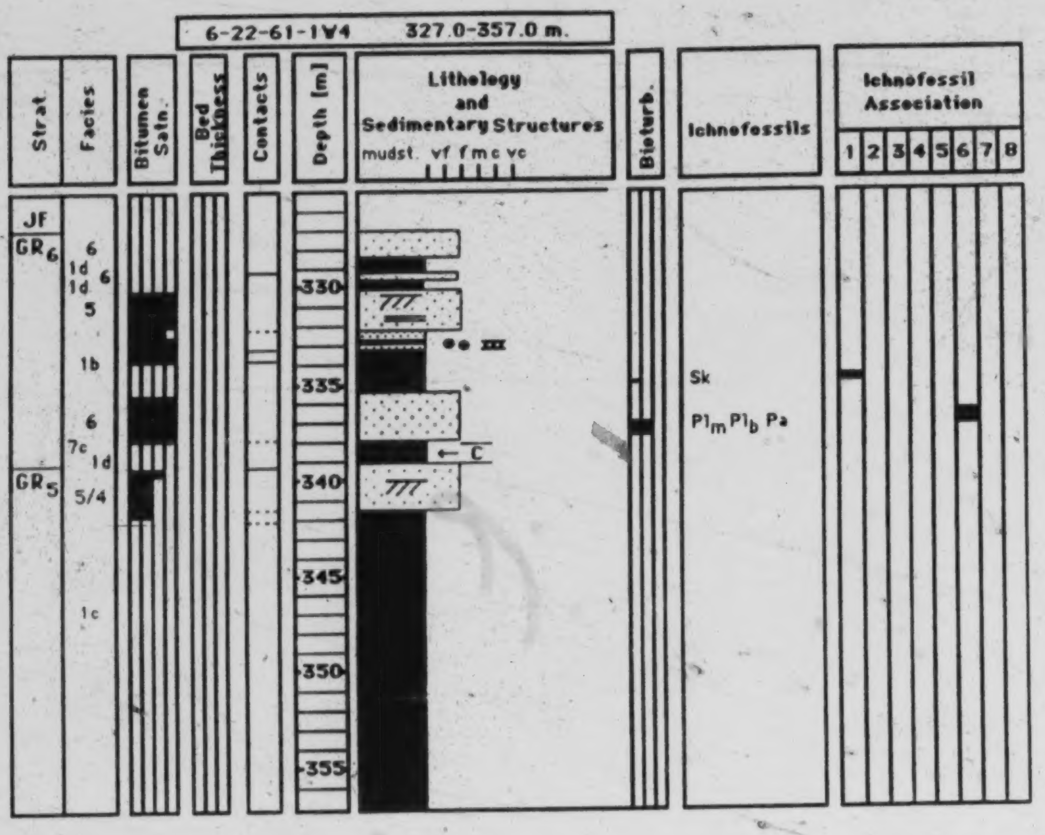
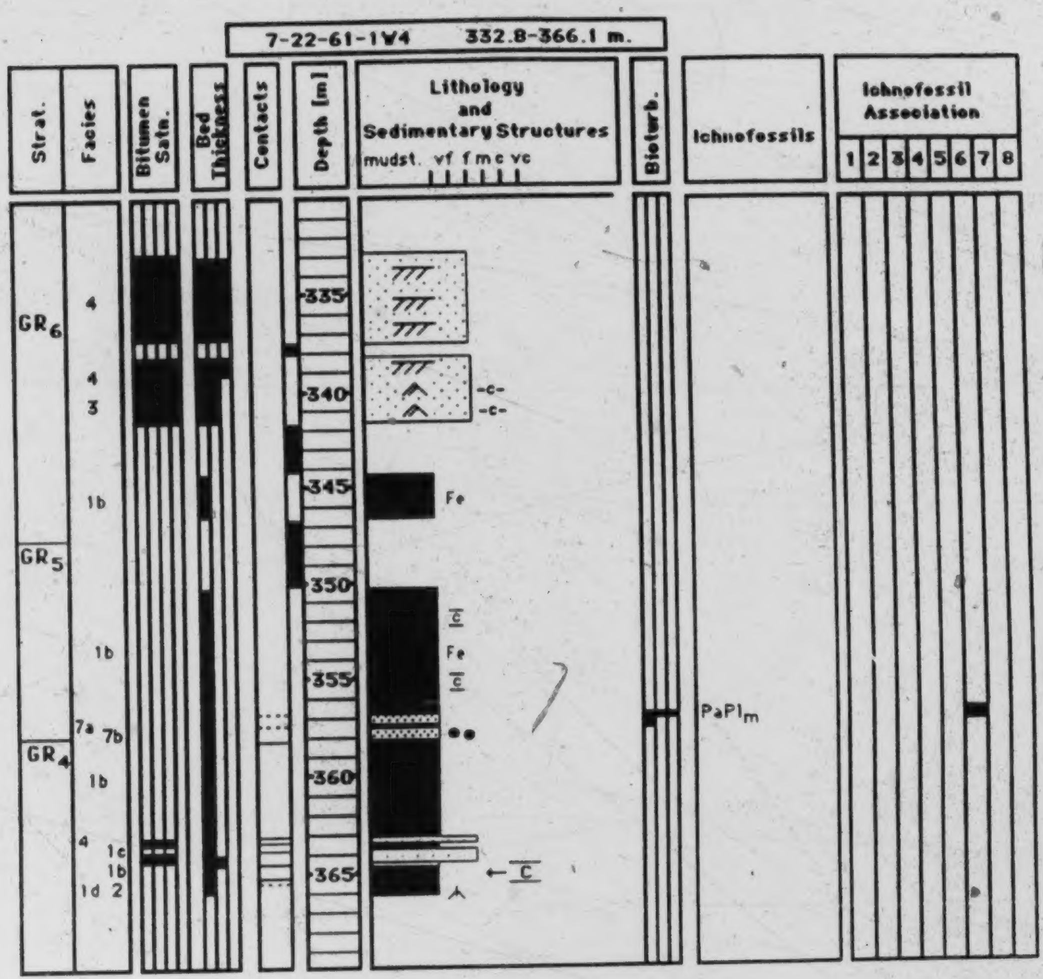
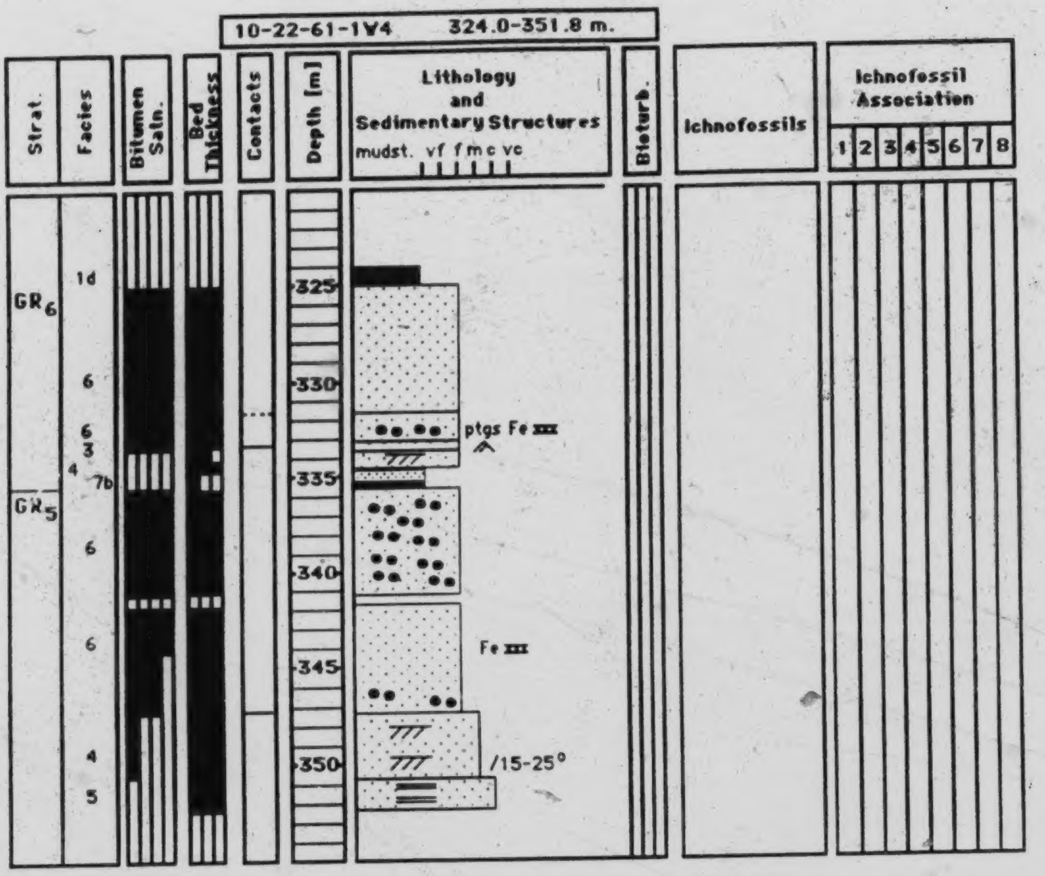
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
330
335
340
345
350
355
JF
GR6
GR5
1a
1c
7a
7b
1c
7b
2
1c
5
1c
1b
1b
-c-
-c-
Pl$_m$ Pa Sk
Pl$_m$ Sk
Pl$_m$ Pa As
Pl$_m$ Pa
Gy Sk Pl$_m$
Pl$_m$ Pa
Pl$_m$
Pl$_m$


7-21-61-1W4 332.0-352.3 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
JF
GR6
GR5
1a
1b
1c
4
2
1b
1c
5
1c
7b
1c
335
340
345
350
ptgs
ptgs
ptgs
Pl_m
Pl_m As Pa Sk
Pl_m
Th(Cy Op Sk)
Gy
Pl_m Pa As
Gy Ro Sk
Pl_m Pa As
Pl_m


6-22-61-1W4 327.0-357.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
JF
GR6
GR5
6
1d
1d
6
5
1b
6
7c
1d
5/4
1c
330
335
340
345
350
355
C
Sk
Pl m Pl b Pa


7-22-61-1W4 332.8-366.1 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
GR4
4
4
3
1b
1b
7a
7b
1b
4
1c
1b
1d
2
335
340
345
350
355
360
365
-c-
-c-
Fe
Fe
c
c
c
PaPl_m


10-22-61-1W4 324.0-351.8 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
1d
6
6
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7b
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325
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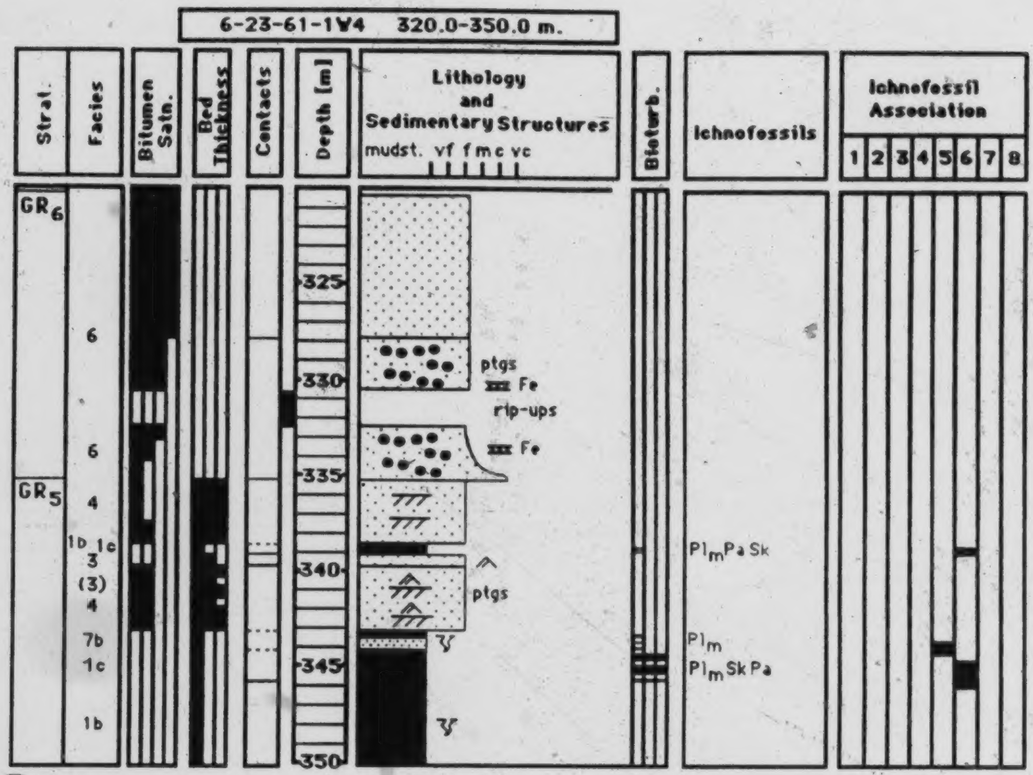
ptgs Fe xxx
Fe xxx
/15-25°


6-23-61-1W4 320.0-350.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
6
6
4
1b 1c
3
(3)
4
7b
1c
1b
325
330
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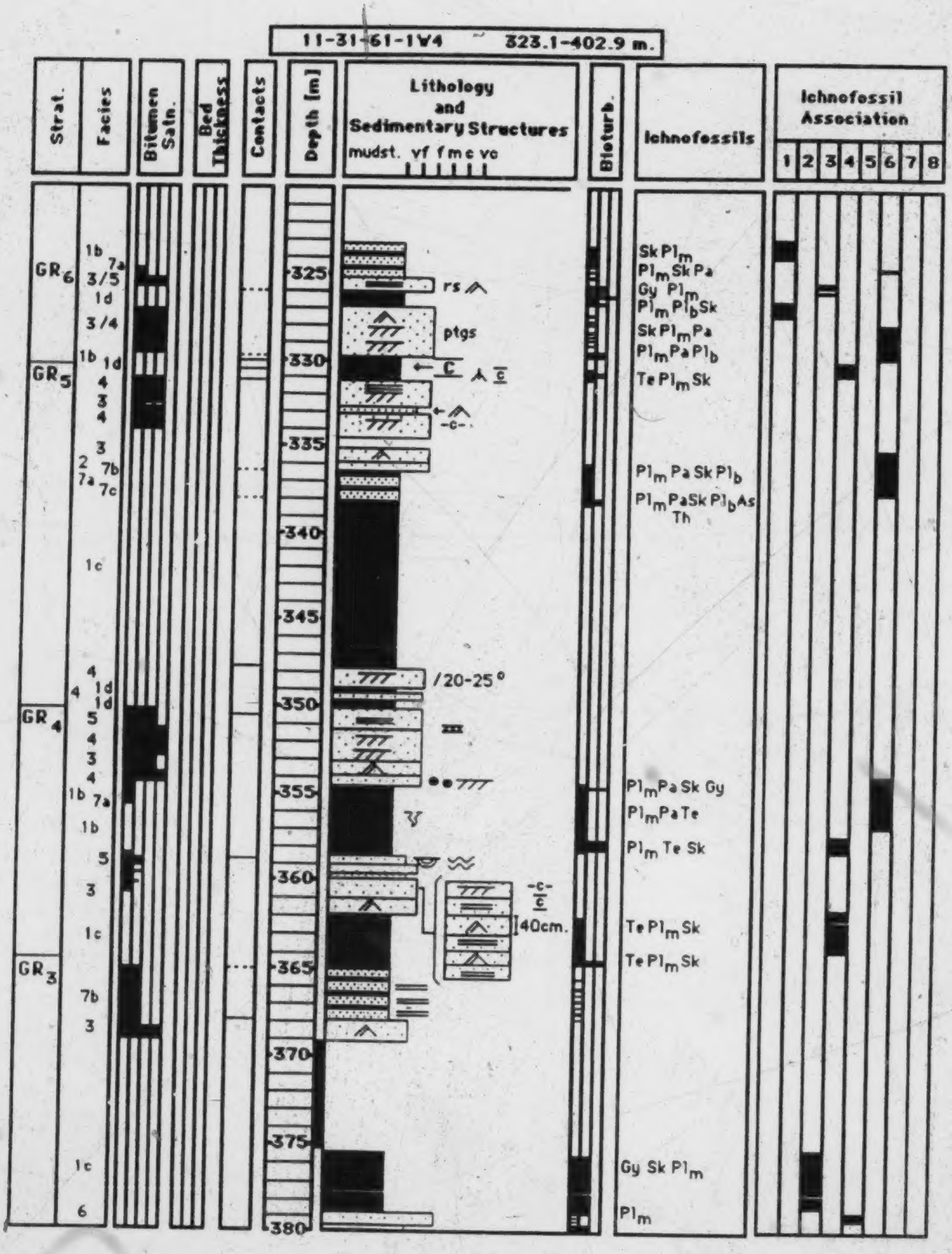
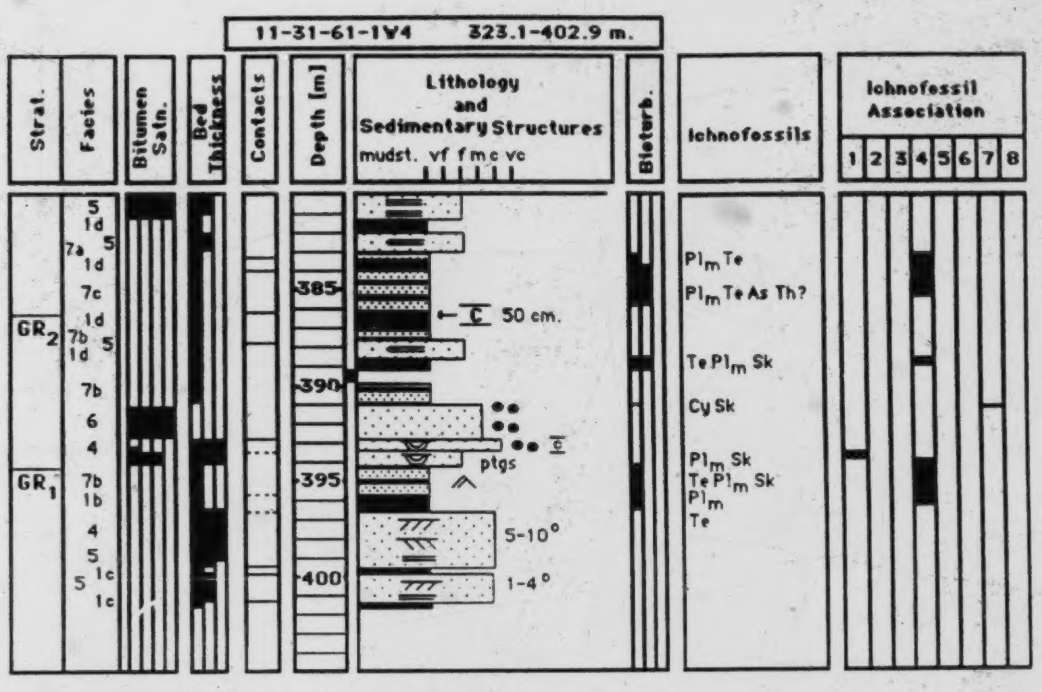
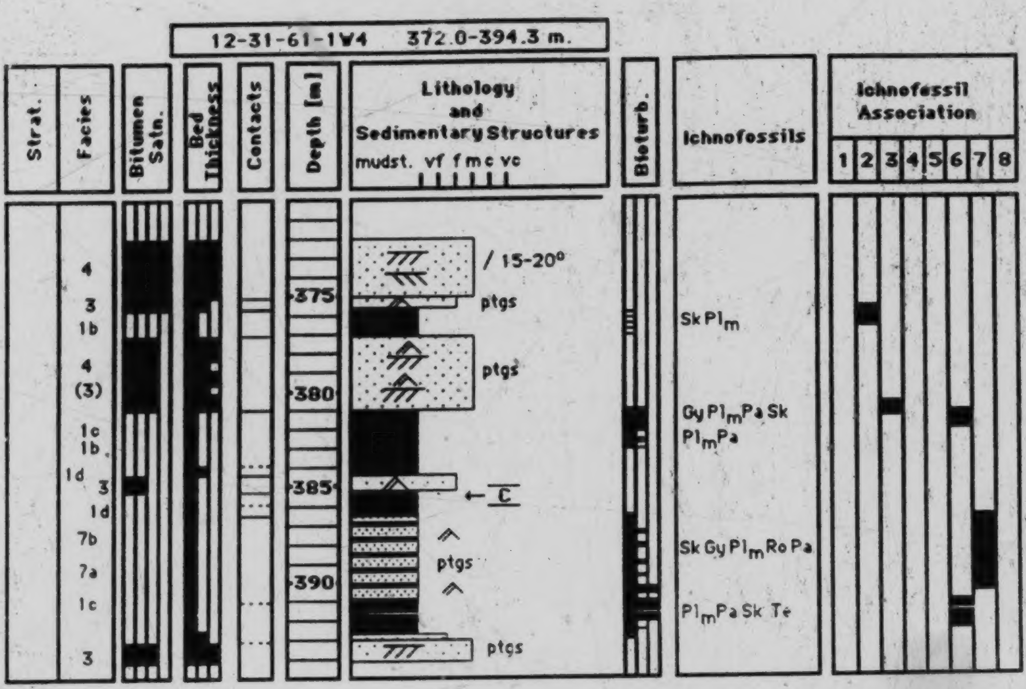
340
345
350
ptgs
Fe
rip-ups
Fe
ptgs
Pl_m Pa Sk
Pl_m
Pl_m Sk Pa


11-31-61-1W4 ~ 323.1-402.9 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
GR4
GR3
1b
7a
3/5
1d
3/4
1b 1d
4
3
4
3
2 7b
7a 7c
1c
4
4 1d
1d
5
4
3
4
1b 7a
1b
5
3
1c
7b
3
1c
6
325
330
335
340
345
350
355
360
365
370
375
380
rs
ptgs
C
-c-
/20-25°
40cm.
Sk Pl_m
Pl_m Sk Pa
Gy Pl_m
Pl_m Pl_b Sk
Sk Pl_m Pa
Pl_m Pa Pl_b
Te Pl_m Sk
Pl_m Pa Sk Pl_b
Pl_m Pa Sk Pl_b As Th
Pl_m Pa Sk Gy
Pl_m Pa Te
Pl_m Te Sk
Te Pl_m Sk
Te Pl_m Sk
Gy Sk Pl_m
Pl_m


11-31-61-1W4 323.1-402.9 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1
2
3
4
5
6
7
8
GR2
GR1
5
1d
7a
5
1d
7c
1d
7b
5
1d
7b
6
4
7b
1b
4
5
5
1c
1c
385
390
395
400
C 50 cm.
c
ptgs
5-10°
1-4°
Pl_m Te
Pl_m Te As Th?
Te Pl_m Sk
Cy Sk
Pl_m Sk
Te Pl_m Sk
Pl_m
Te


12-31-61-1W4 372.0-394.3 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
4
3
1b
4
(3)
1c
1b
1d
3
1d
7b
7a
1c
3
375
380
385
390
/ 15-20°
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C
ptgs
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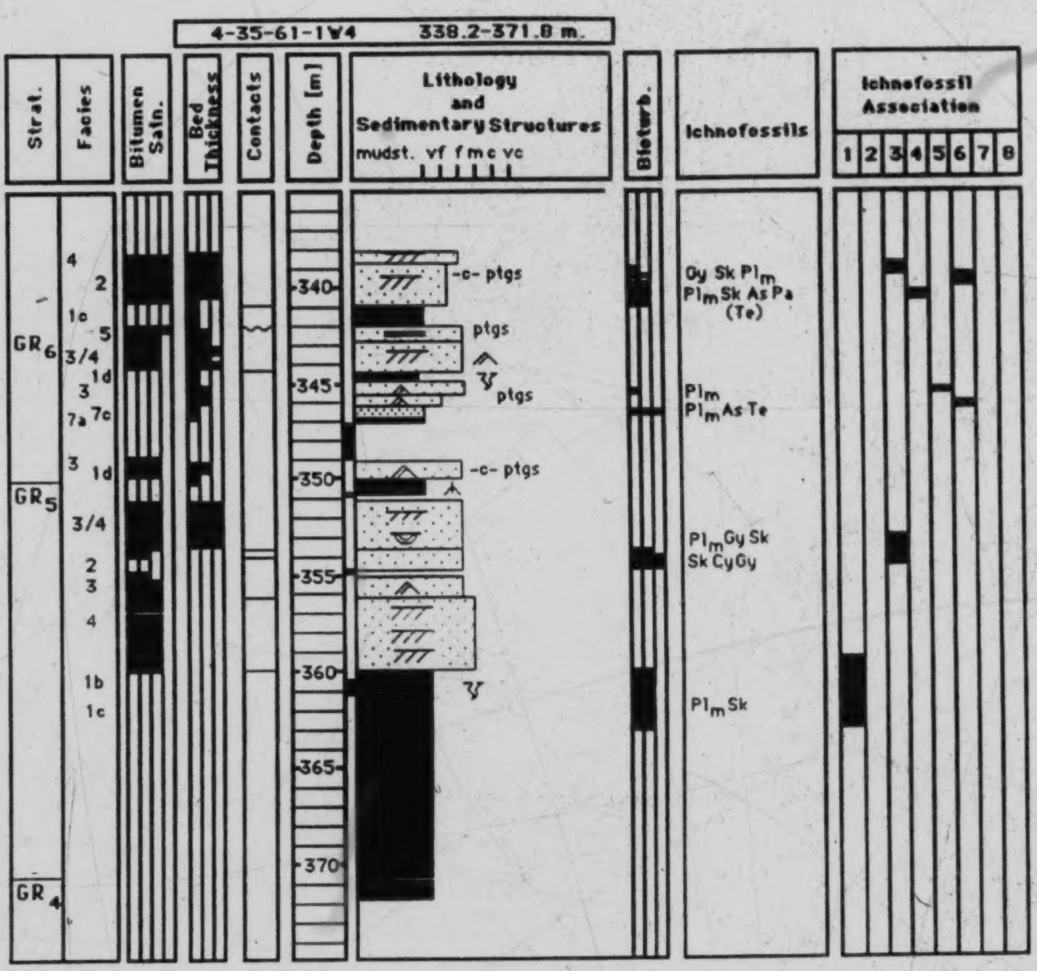
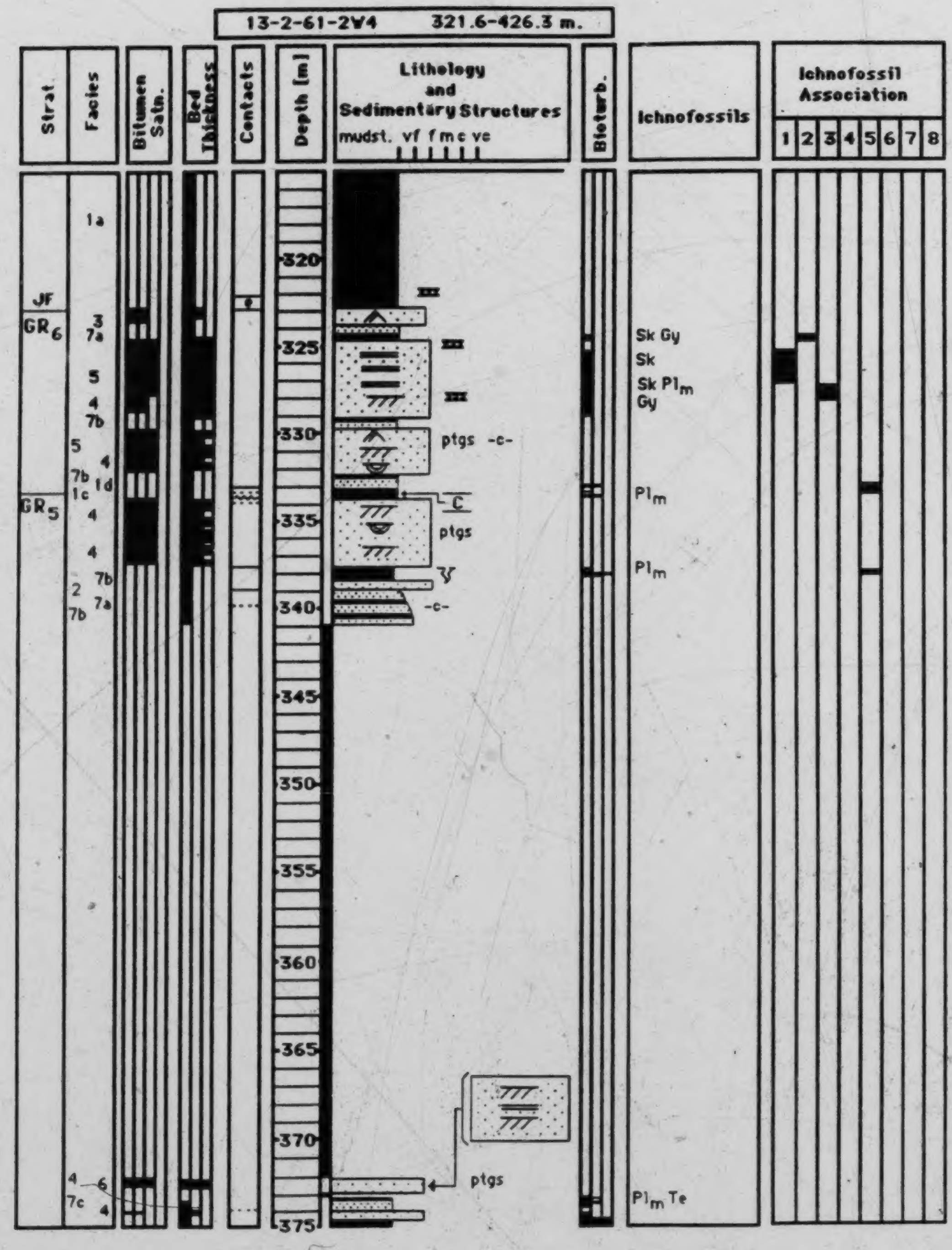
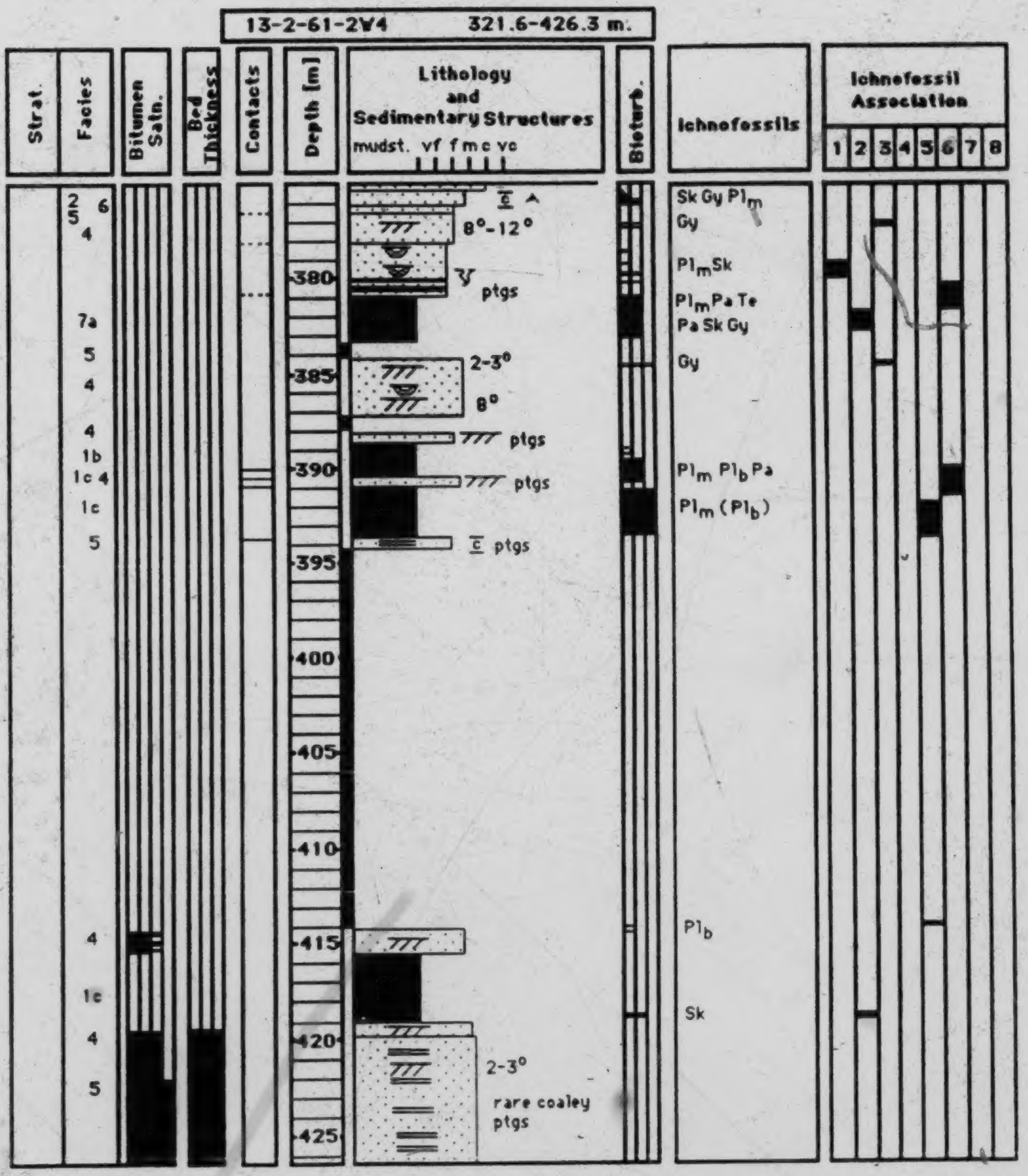
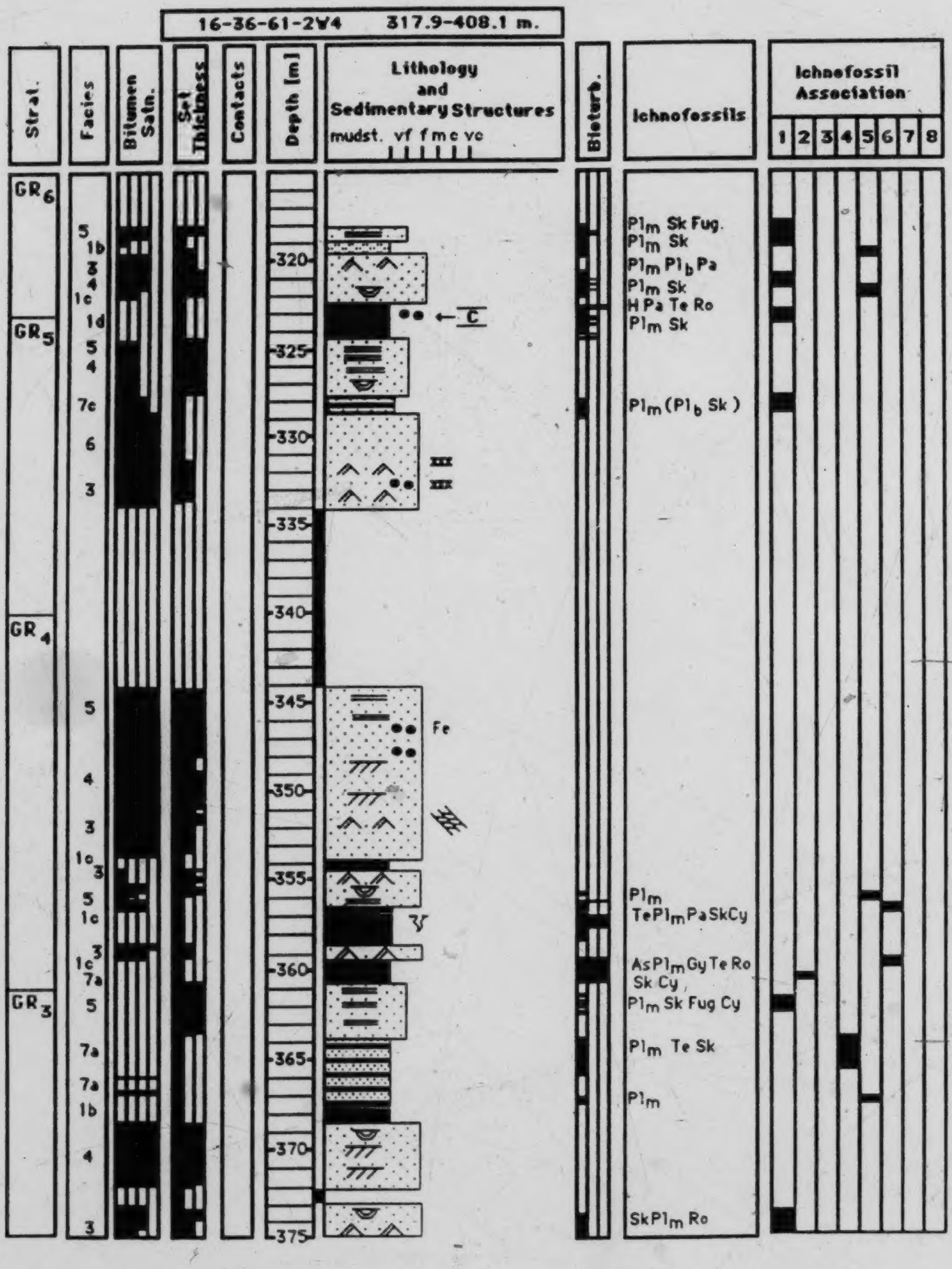
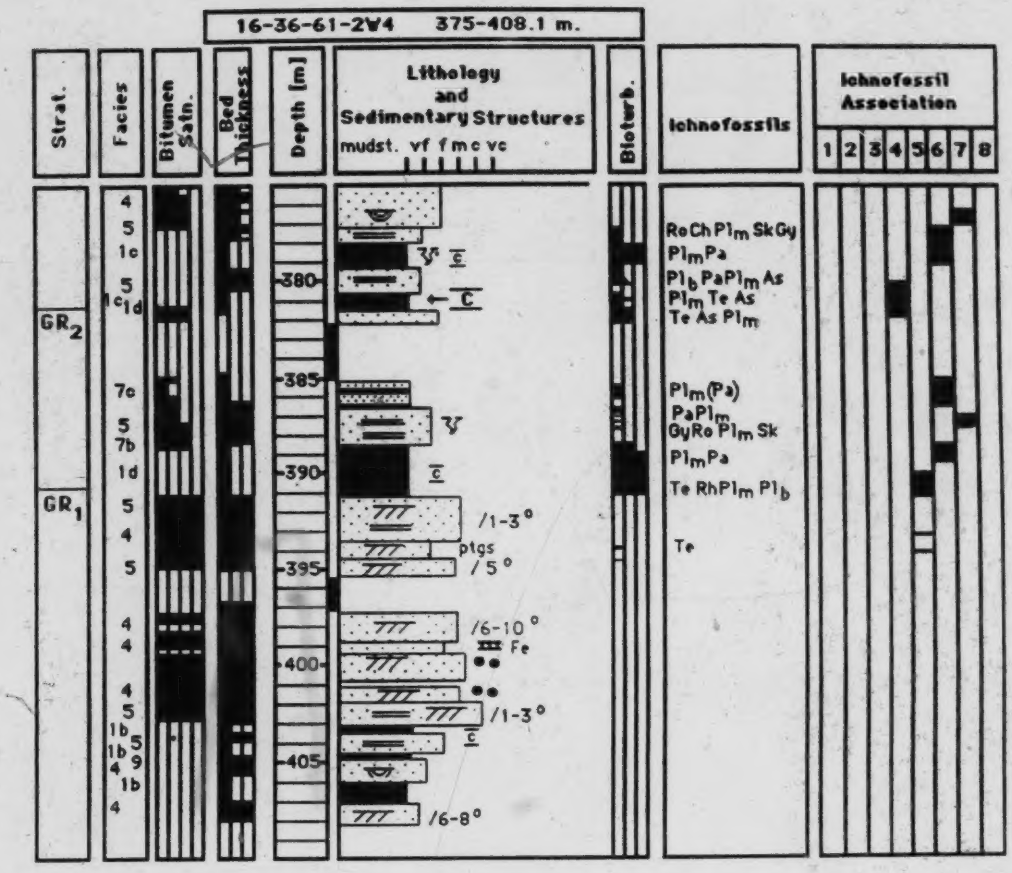
Sk Gy Pl_m Ro Pa
Pl_m Pa Sk Te

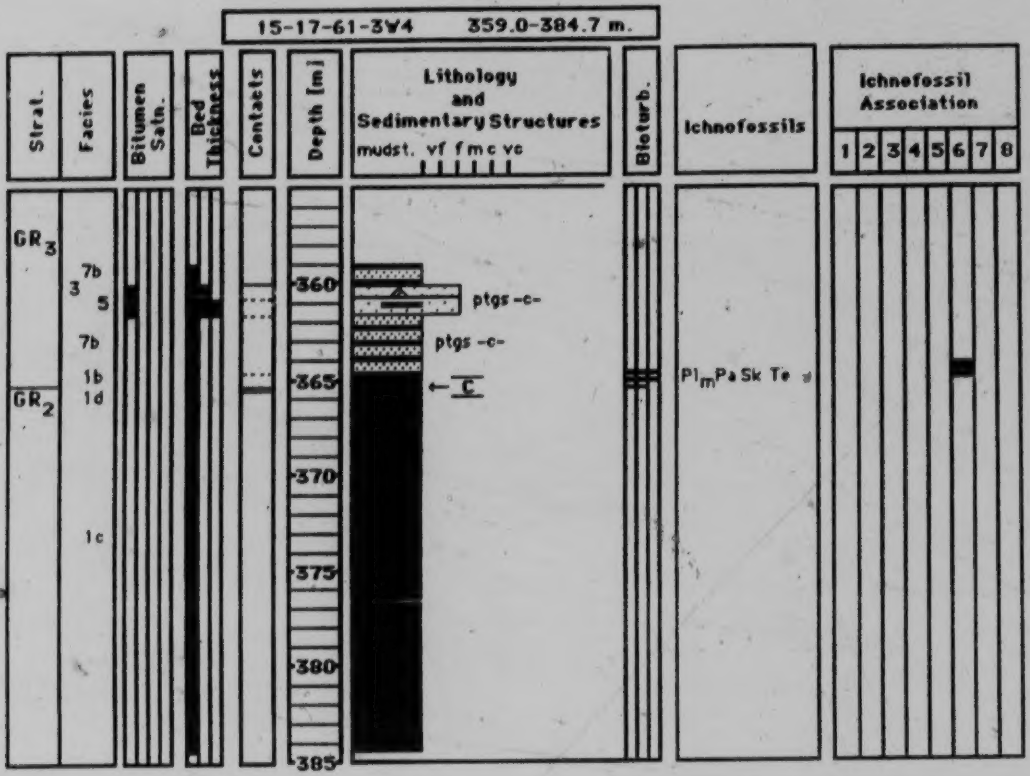

4-35-61-1W4 338.2-371.8 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
GR4
4
2
1c
5
3/4
1d
3
7a
7c
3
1d
3/4
2
3
4
1b
1c
340
345
350
355
360
365
370
-c- ptgs
ptgs
ptgs
-c- ptgs
Gy Sk Plm
Plm Sk As Pa
(Te)
Plm
Plm As Te
Plm Gy Sk
Sk Cy Gy
Plm Sk

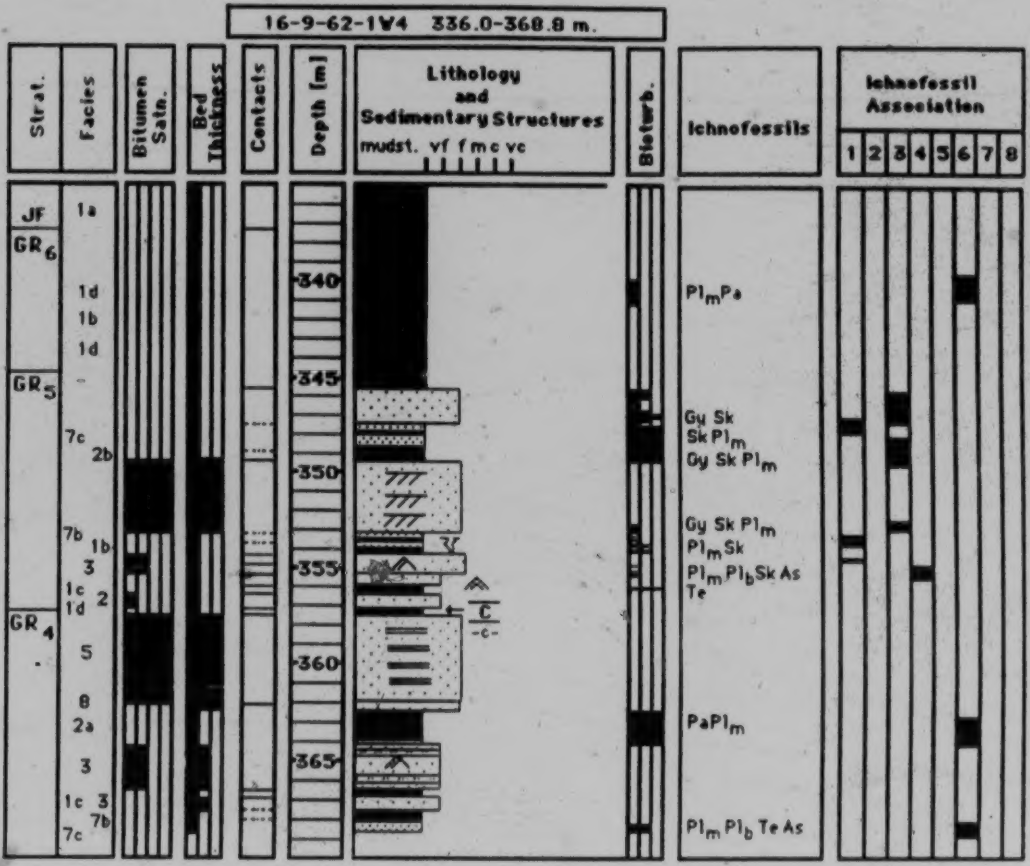

13-2-61-2W4 321.6-426.3 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
JF
GR6
GR5
1a
3
7a
5
4
7b
5
4
7b
1c
1d
4
4
7b
2
7a
7b
4
6
7c
4
320
325
330
335
340
345
350
355
360
365
370
375
ptgs -c-
C
ptgs
-c-
ptgs
Sk Gy
Sk
Sk Pl
m
Gy
Pl
m
Pl
m
Pl
m
Te

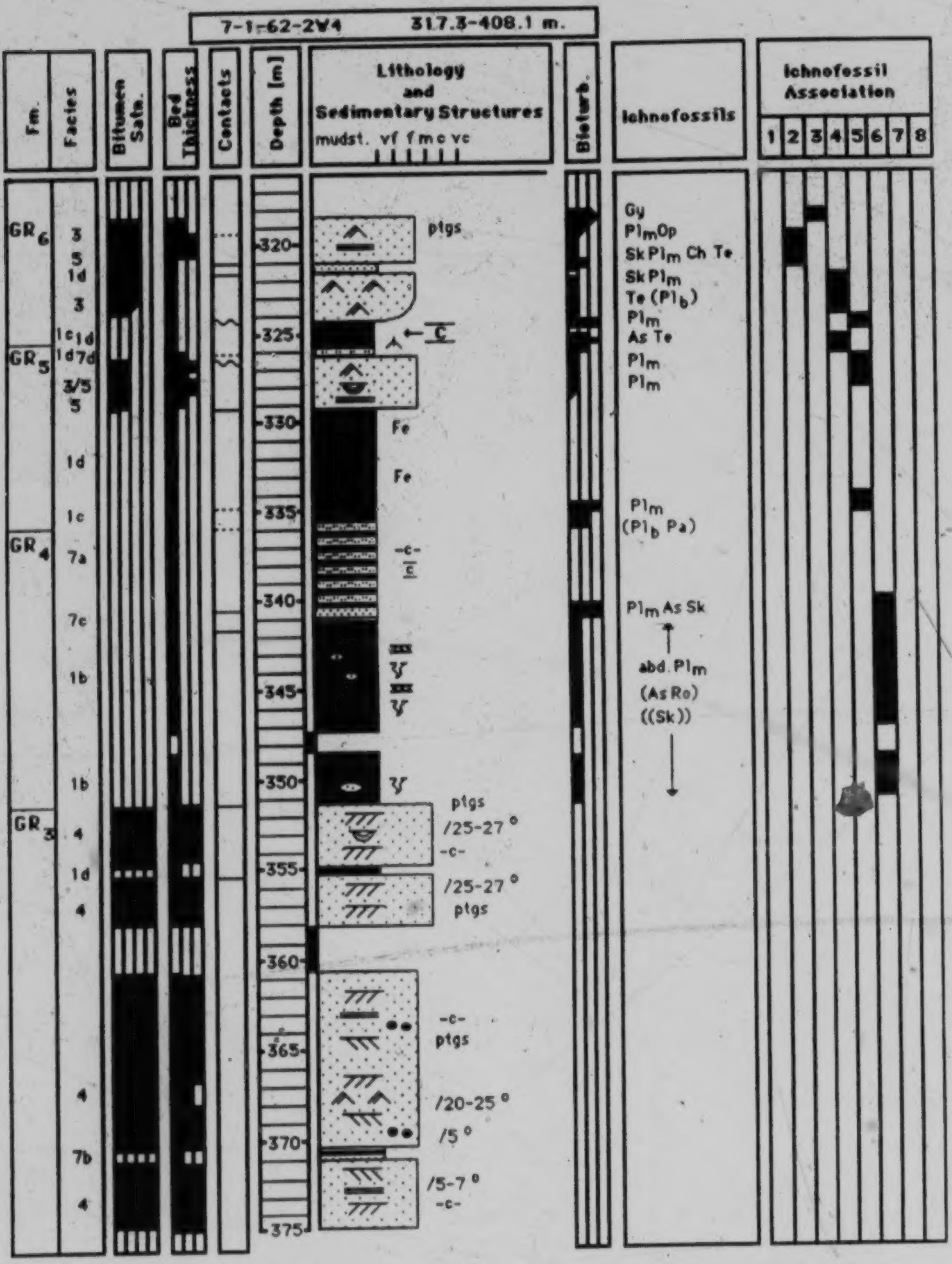

13-2-61-2W4 321.6-426.3 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
2 5 6
4
7a
5
4
4
1b
1c 4
1c
5
4
1c
4
5
380
385
390
395
400
405
410
415
420
425
8°-12°
ptgs
2-3°
8°
ptgs
ptgs
ptgs
2-3°
rare coaley
ptgs
Sk Gy Pl$_m$
Gy
Pl$_m$ Sk
Pl$_m$ Pa Te
Pa Sk Gy
Gy
Pl$_m$ Pl$_b$ Pa
Pl$_m$ (Pl$_b$)
Pl$_b$
Sk

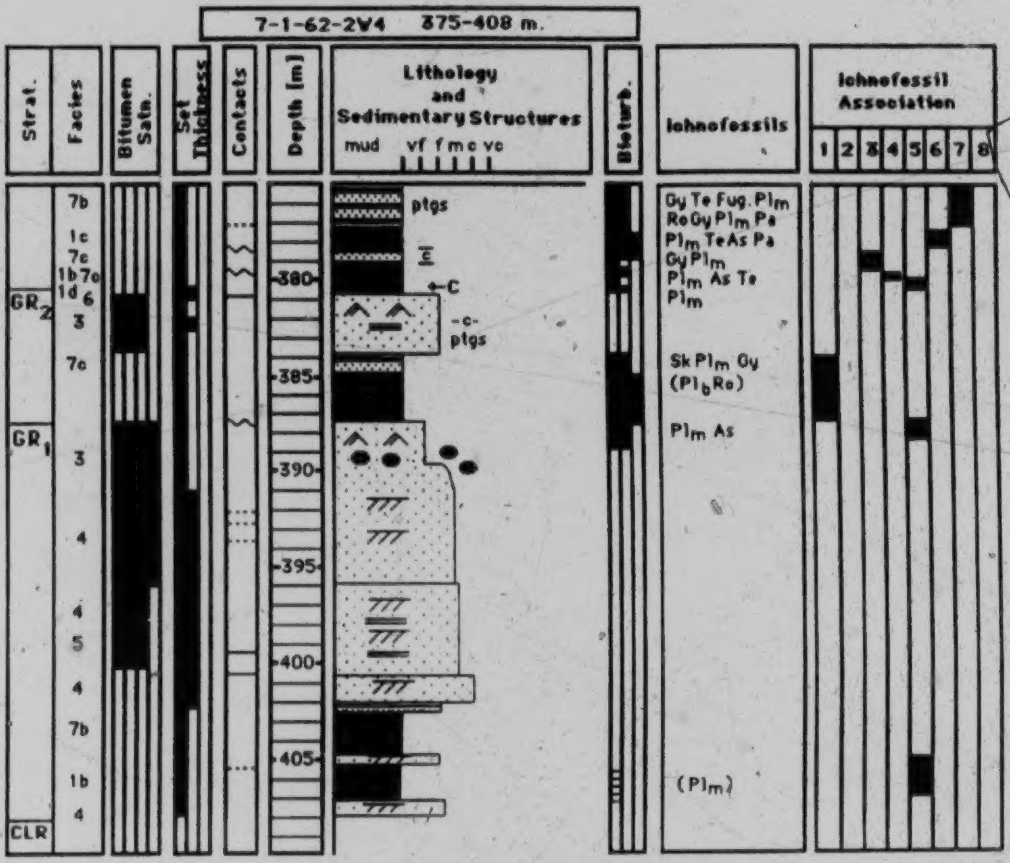

16-36-61-2W4 317.9-408.1 m.
Strat.
Facies
Bitumen Satn.
Set Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
GR4
GR3
5
1b
3
4
1c
1d
5
4
7c
6
3
5
4
3
1c
3
5
1c
3
1c
7a
5
7a
7a
1b
4
3
320
325
330
335
340
345
350
355
360
365
370
375
C
Fe
Pl m Sk Fug.
Pl m Sk
Pl m Pl b Pa
Pl m Sk
H Pa Te Ro
Pl m Sk
Pl m (Pl b Sk)
Pl m
TePl m PaSkCy
AsPl m Gy Te Ro
Sk Cy
Pl m Sk Fug Cy
Pl m Te Sk
Pl m
SkPl m Ro

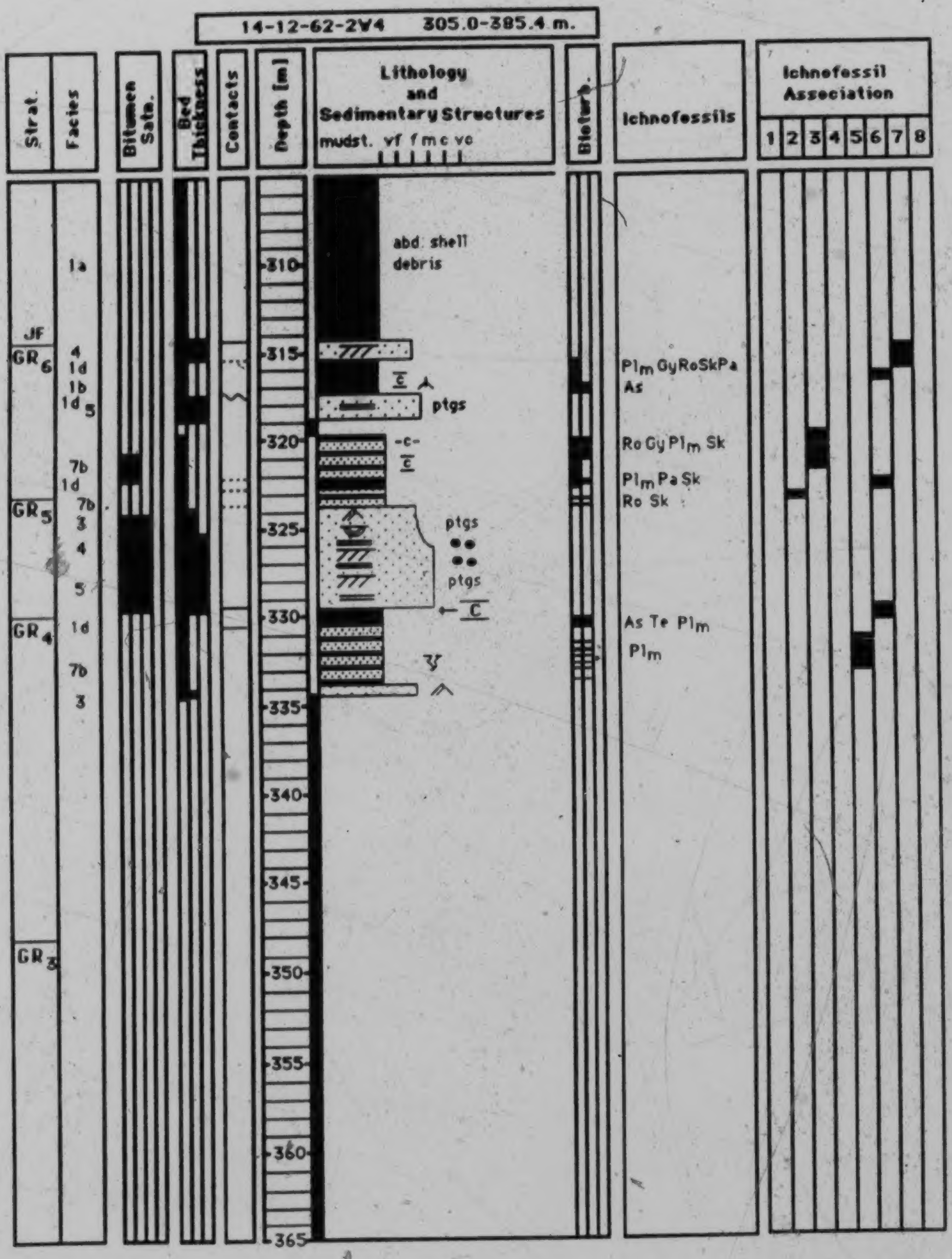

16-36-61-2W4 375-408.1 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR2
GR1
4
5
1c
5
1c 1d
7c
5
7b
1d
5
4
5
4
4
4
5
1b 5
1b 9
4
1b
4
380
385
390
395
400
405
c
c
c
c
/1-3°
ptgs
/5°
/6-10°
Fe
/1-3°
/6-8°
Ro Ch Pl_m Sk Gy
Pl_m Pa
Pl_b Pa Pl_m As
Pl_m Te As
Te As Pl_m
Pl_m (Pa)
Pa Pl_m
Gy Ro Pl_m Sk
Pl_m Pa
Te Rh Pl_m Pl_b
Te

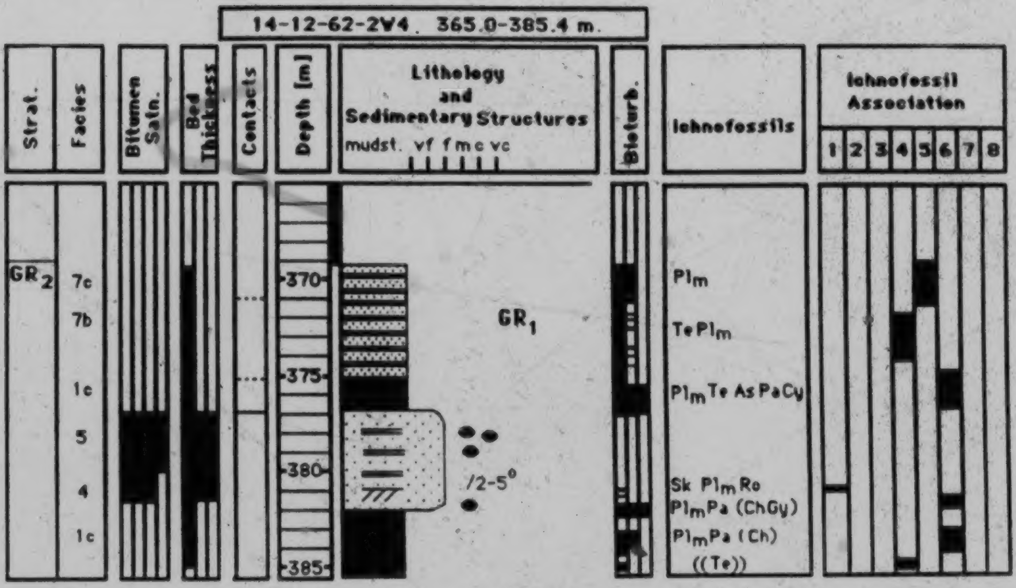

15-17-61-3W4 359.0-384.7 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1
2
3
4
5
6
7
8
GR3
GR2
7b
3
5
7b
1b
1d
1c
360
365
370
375
380
385
ptgs -c-
ptgs -c-
C
Pl m Pa Sk Te

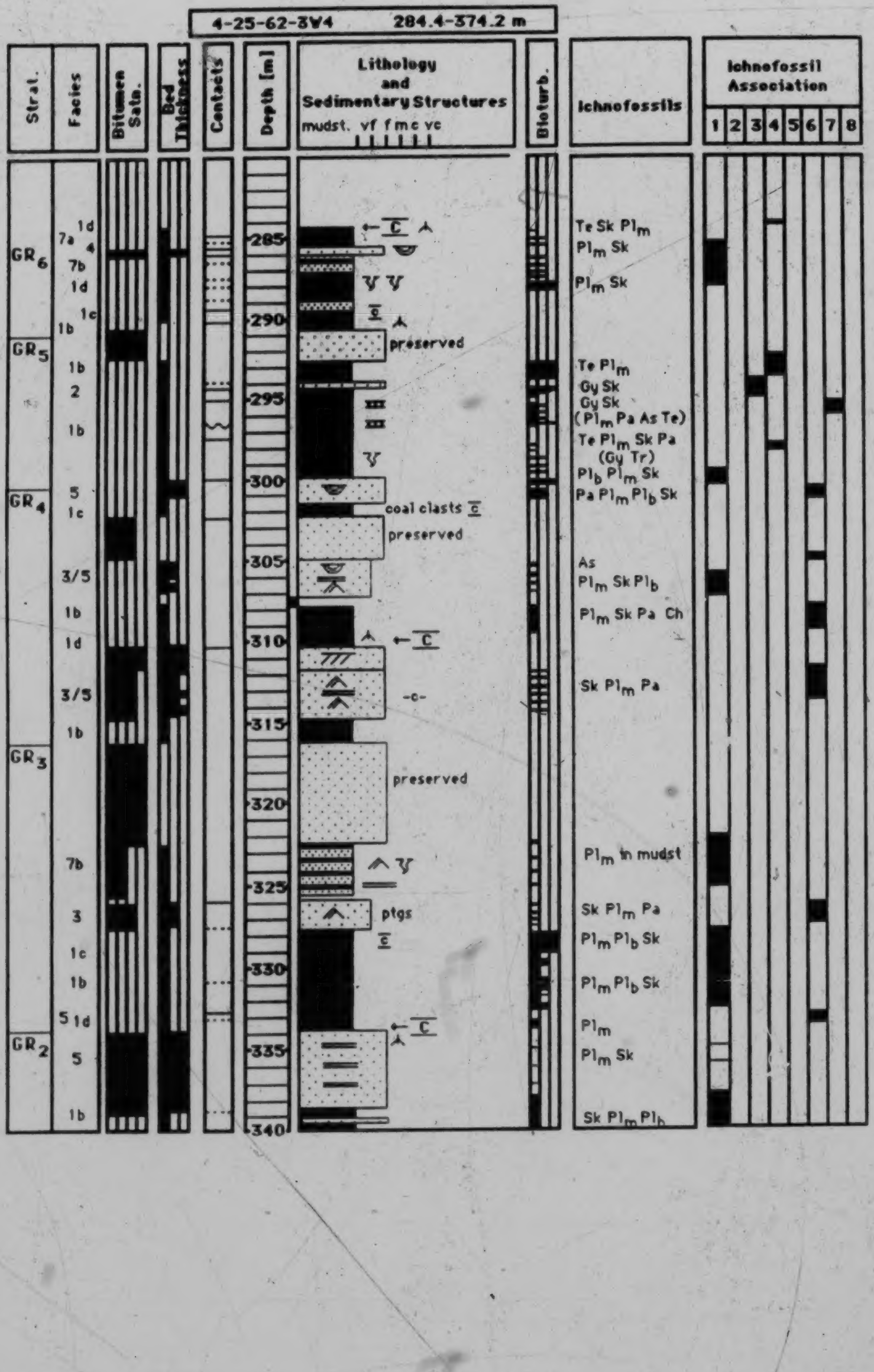

16-9-62-1W4 336.0-368.8 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
JF
GR6
GR5
GR4
1a
1d
1b
1d
7c
2b
7b
1b
3
1c
2
1d
5
8
2a
3
1c
3
7b
7c
340
345
350
355
360
365
C
-c-
PlmPa
Gy Sk
Sk Plm
Gy Sk Plm
Gy Sk Plm
Plm Sk
Plm Plb Sk As Te
PaPlm
Plm Plb Te As

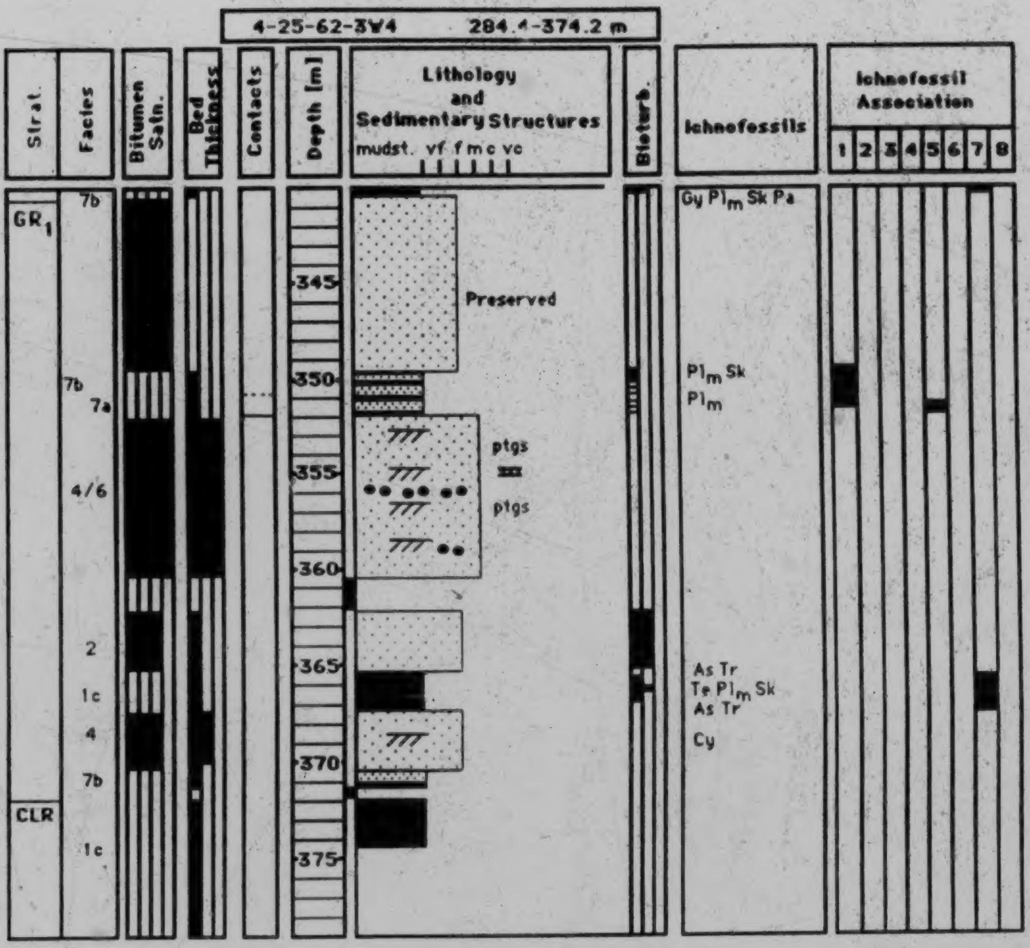

7-1-62-2W4 317.3-408.1 m.
Fm.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
GR4
GR3
3
5
1d
3
1c1d
1d7d
3/5
5
1d
1c
7a
7c
1b
1b
4
1d
4
4
7b
4
320
325
330
335
340
345
350
355
360
365
370
375
ptgs
C
Fe
Fe
-c-
c
ptgs
/25-27 °
-c-
/25-27 °
ptgs
-c-
ptgs
/20-25 °
/5 °
/5-7 °
-c-
Gy
PlmOp
Sk Plm Ch Te
Sk Plm
Te (Plb)
Plm
As Te
Plm
Plm
Plm
(Plb Pa)
Plm As Sk
abd. Plm
(As Ro)
((Sk))

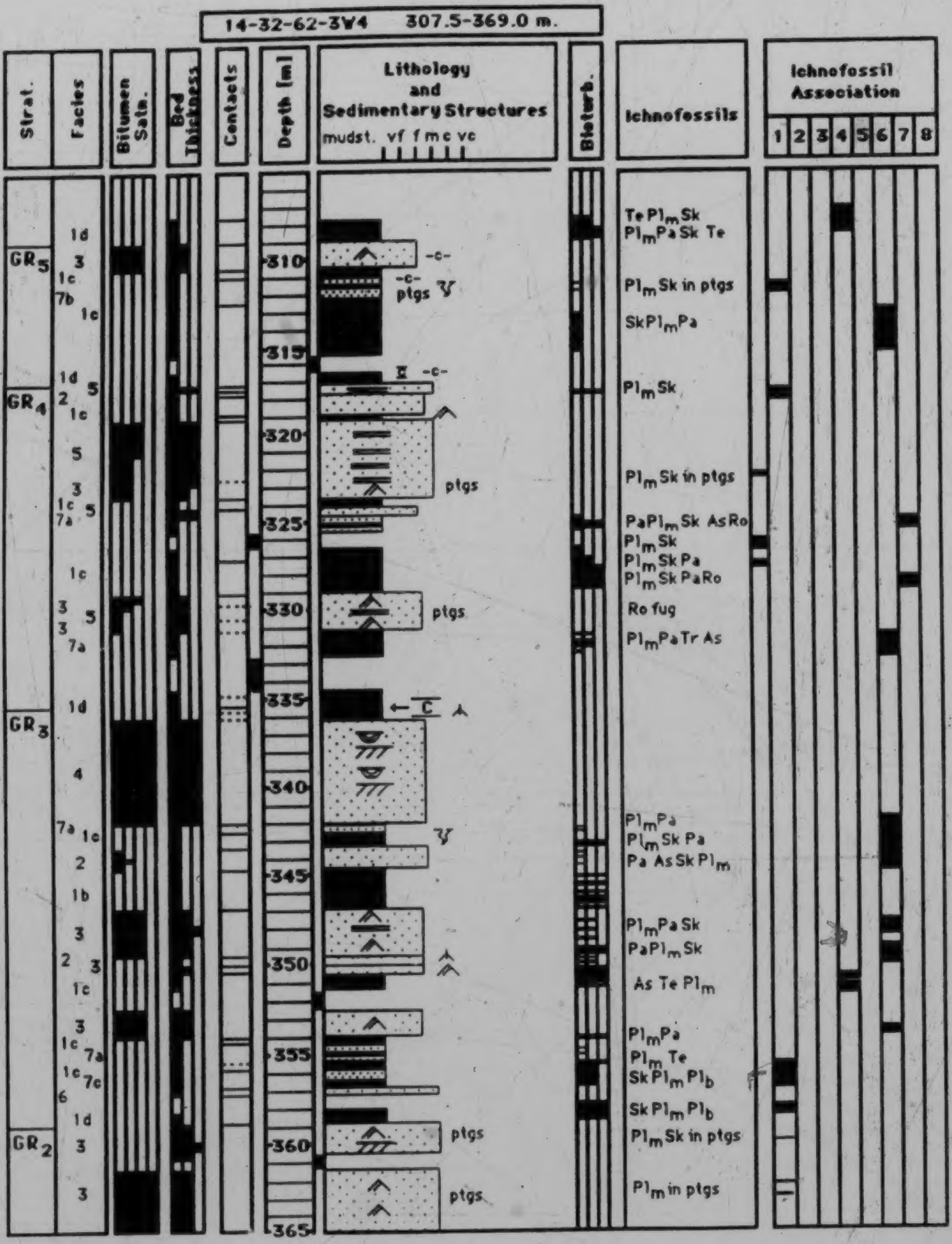

7-1-62-2W4 375-408 m.
Strat.
Facies
Bitumen Satn.
Set Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mud vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR2
GR1
CLR
7b
1c
7c
1b 7c
1d 6
3
7c
3
4
4
5
4
7b
1b
4
380
385
390
395
400
405
ptgs
C
-c-
ptgs
Gy Te Fug. Pl$_m$
Ro Gy Pl$_m$ Pa
Pl$_m$ Te As Pa
Gy Pl$_m$
Pl$_m$ As Te
Pl$_m$
Sk Pl$_m$ Gy
(Pl$_b$ Ro)
Pl$_m$ As
(Pl$_m$)

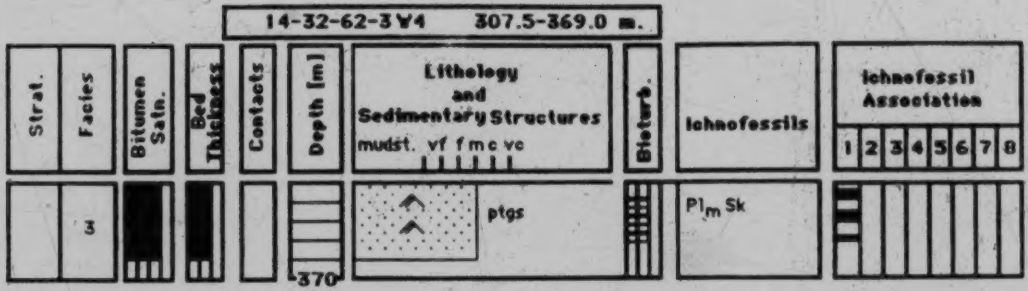

14-12-62-2W4 305.0-385.4 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
JF
GR6
GR5
GR4
GR3
1a
4
1d
1b
1d 5
7b
1d
7b
3
4
5
1d
7b
3
310
315
320
325
330
335
340
345
350
355
360
365
abd. shell debris
ptgs
-c-
ptgs
ptgs
C
Plm GyRoSkPa As
Ro Gy Plm Sk
Plm Pa Sk
Ro Sk
As Te Plm
Plm

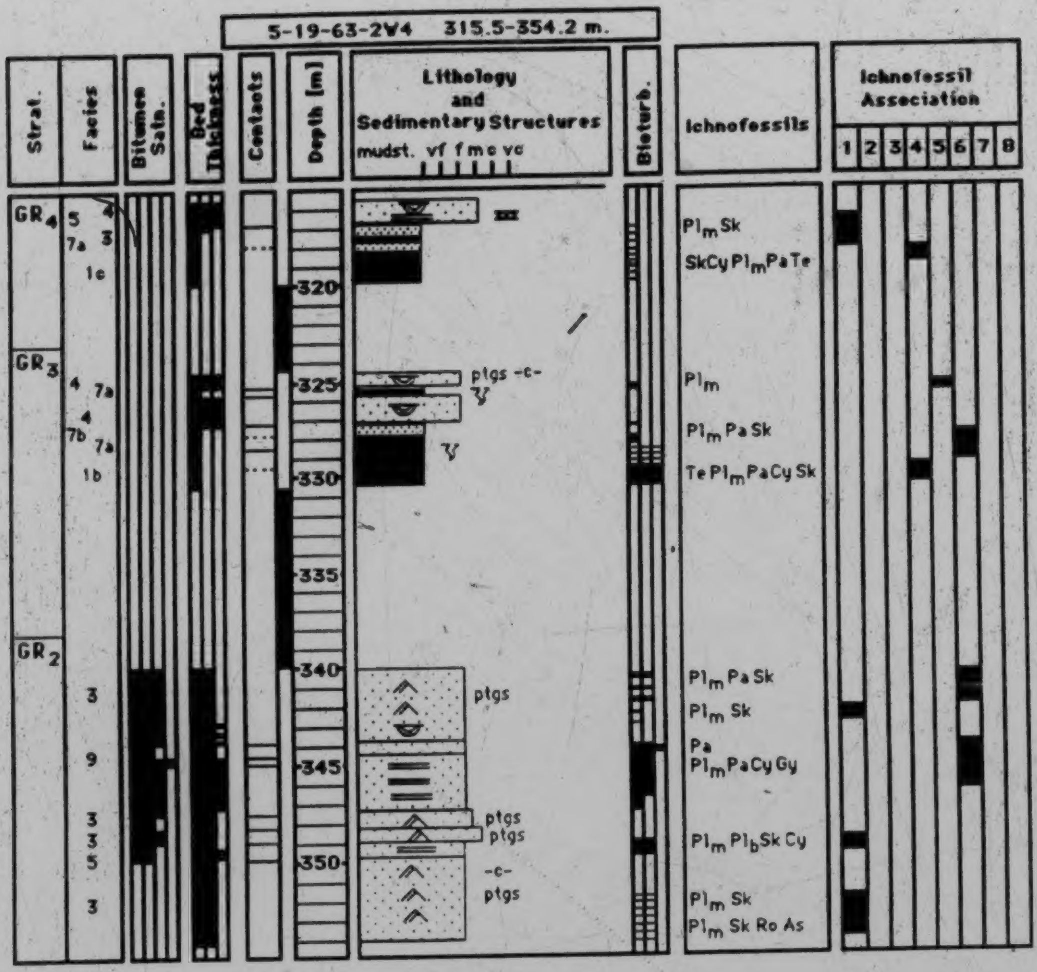

14-12-62-2W4. 365.0-385.4 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR2
7c
7b
1c
5
4
1c
370
375
380
385
GR1
/2-5°
Plm
Te Plm
Plm Te As Pa Cy
Sk Plm Ro
Plm Pa (ChGy)
Plm Pa (Ch)
((Te))

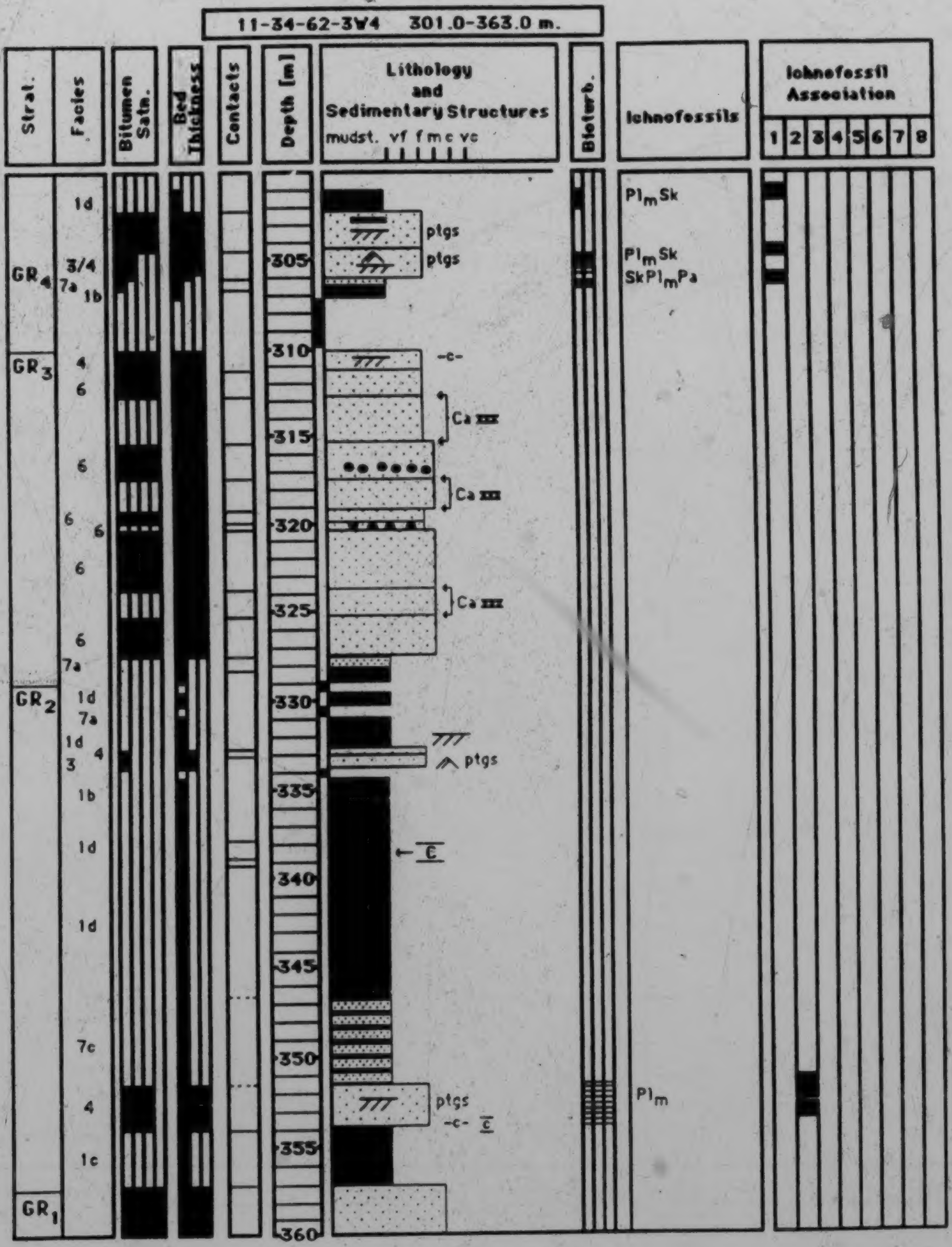

4-25-62-3W4 284.4-374.2 m
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR6
GR5
GR4
GR3
GR2
1d
7a
4
7b
1d
1c
1b
1b
2
1b
5
1c
3/5
1b
1d
3/5
1b
7b
3
1c
1b
5 1d
5
1b
285
290
295
300
305
310
315
320
325
330
335
340
preserved
coal clasts
preserved
-c-
preserved
ptgs
Te Sk Pl_m
Pl_m Sk
Pl_m Sk
Te Pl_m
Gy Sk
Gy Sk
(Pl_m Pa As Te)
Te Pl_m Sk Pa
(Gy Tr)
Pl_b Pl_m Sk
Pa Pl_m Pl_b Sk
As
Pl_m Sk Pl_b
Pl_m Sk Pa Ch
Sk Pl_m Pa
Pl_m in mudst
Sk Pl_m Pa
Pl_m Pl_b Sk
Pl_m Pl_b Sk
Pl_m
Pl_m Sk
Sk Pl_m Pl_b

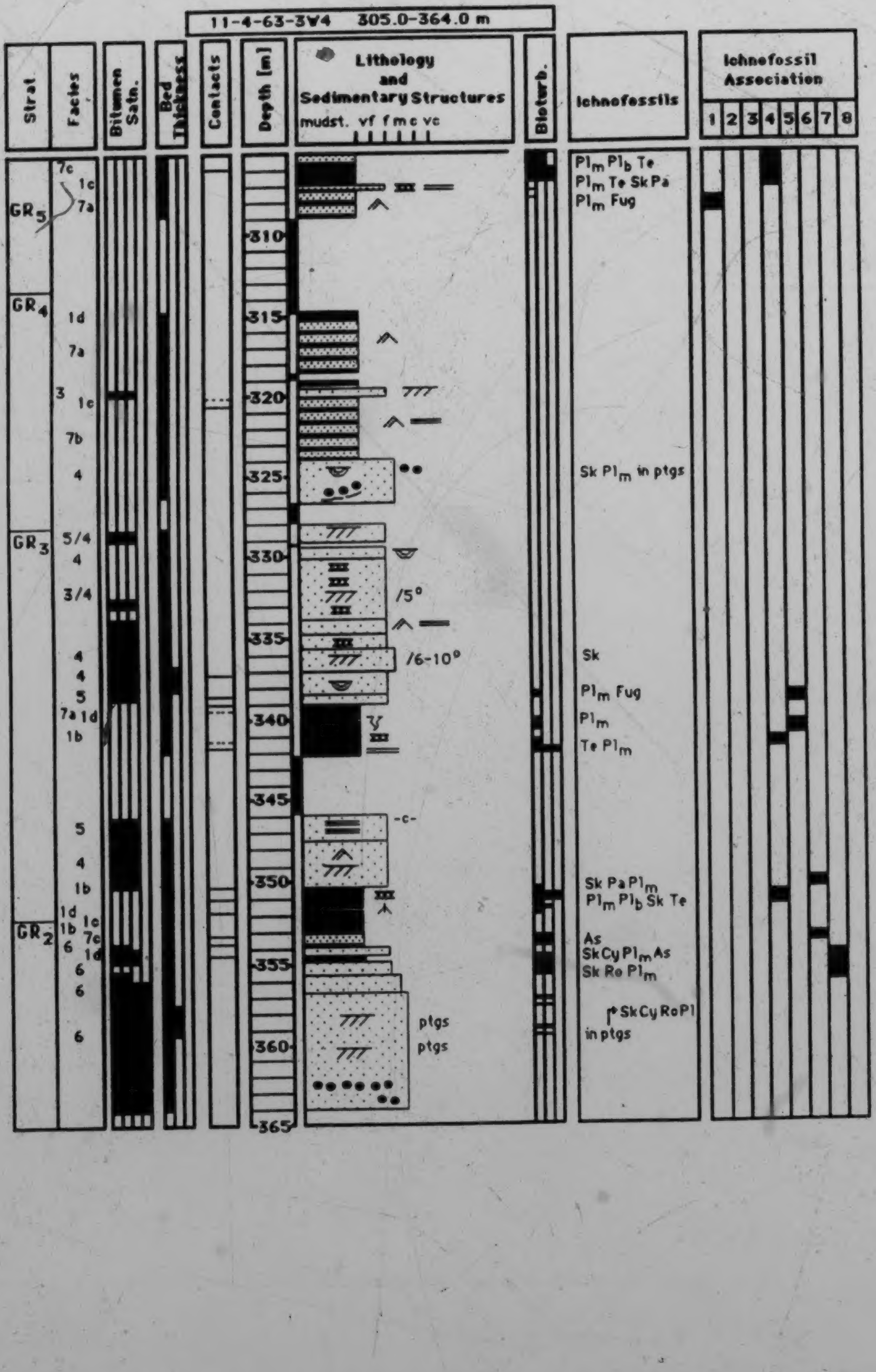

4-25-62-3W4 284.4-374.2 m
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR1
CLR
7b
7b
7a
4/6
2
1c
4
7b
1c
345
350
355
360
365
370
375
Preserved
ptgs
ptgs
Gy Pl$_m$ Sk Pa
Pl$_m$ Sk
Pl$_m$
As Tr
Te Pl$_m$ Sk
As Tr
Cy

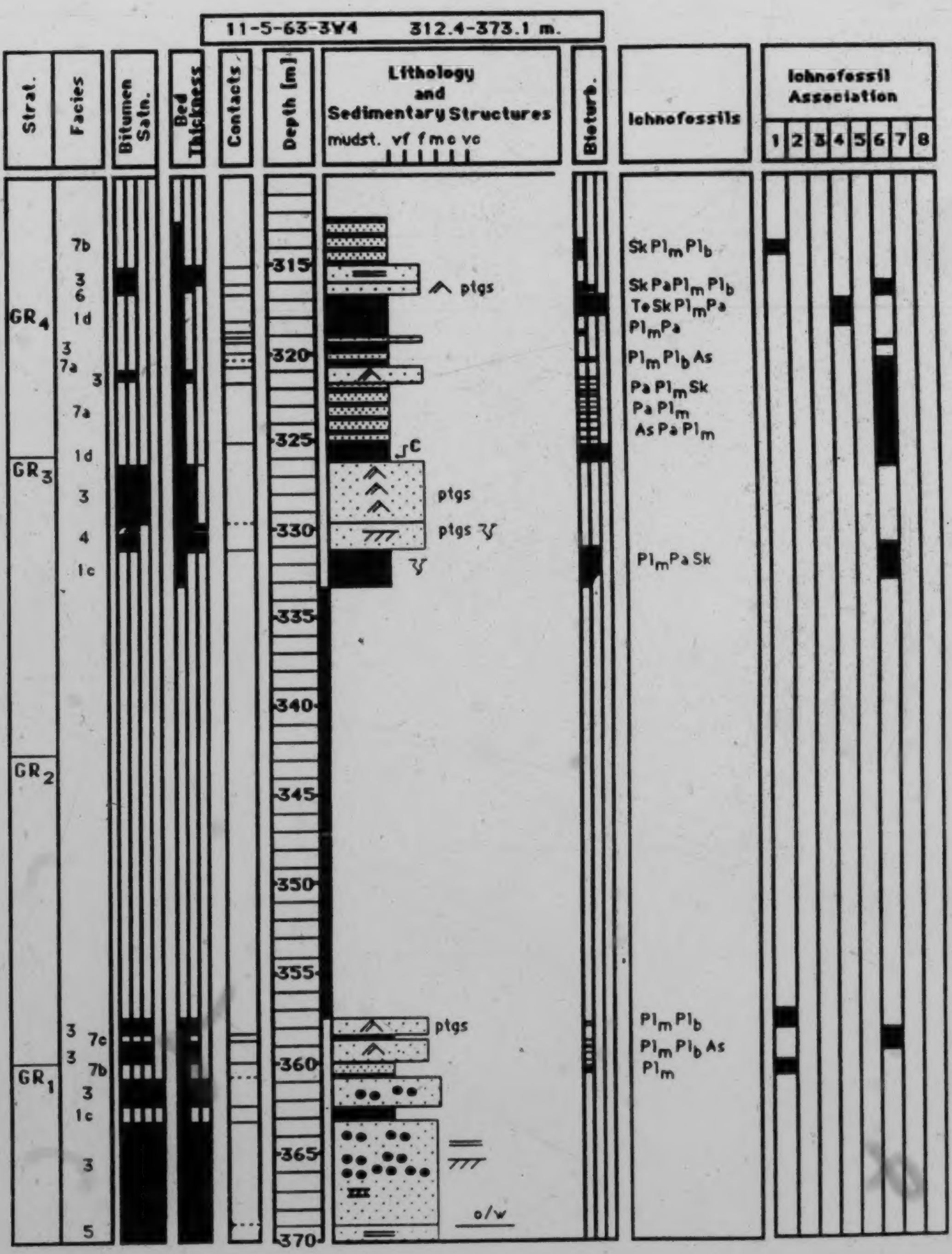

14-32-62-3W4 307.5-369.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR5
GR4
GR3
GR2
1d
3
1c
7b
1c
1d
5
2
1c
5
3
1c
7a
5
1c
3
5
3
7a
1d
4
7a
1c
2
1b
3
2
3
1c
3
1c
7a
1c
7c
6
1d
3
3
310
315
320
325
330
335
340
345
350
355
360
365
-c-
-c-
ptgs
-c-
ptgs
ptgs
C
ptgs
ptgs
Te Pl_m Sk
Pl_m Pa Sk Te
Pl_m Sk in ptgs
Sk Pl_m Pa
Pl_m Sk
Pl_m Sk in ptgs
Pa Pl_m Sk As Ro
Pl_m Sk
Pl_m Sk Pa
Pl_m Sk Pa Ro
Ro fug
Pl_m Pa Tr As
Pl_m Pa
Pl_m Sk Pa
Pa As Sk Pl_m
Pl_m Pa Sk
Pa Pl_m Sk
As Te Pl_m
Pl_m Pa
Pl_m Te
Sk Pl_m Pl_b
Sk Pl_m Pl_b
Pl_m Sk in ptgs
Pl_m in ptgs

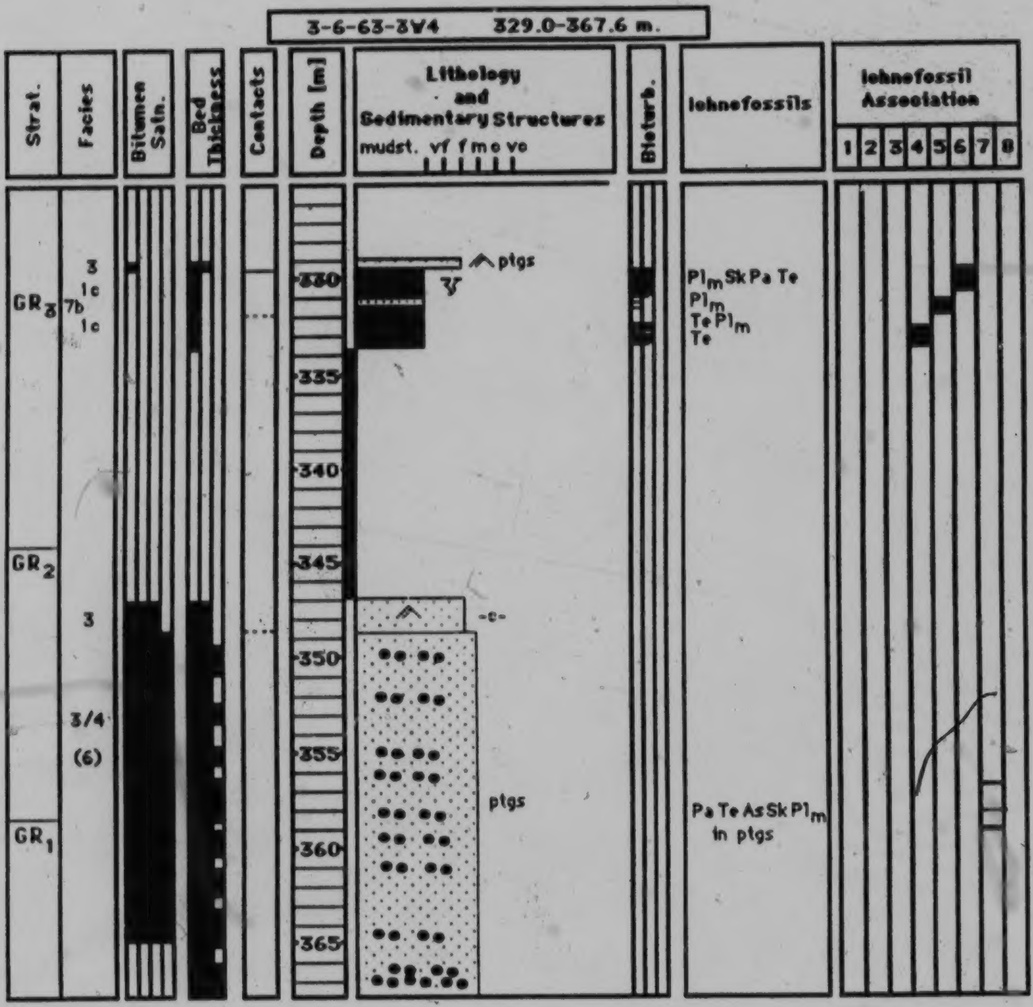

14-32-62-3W4 307.5-369.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
3
370
ptgs
Pl m Sk

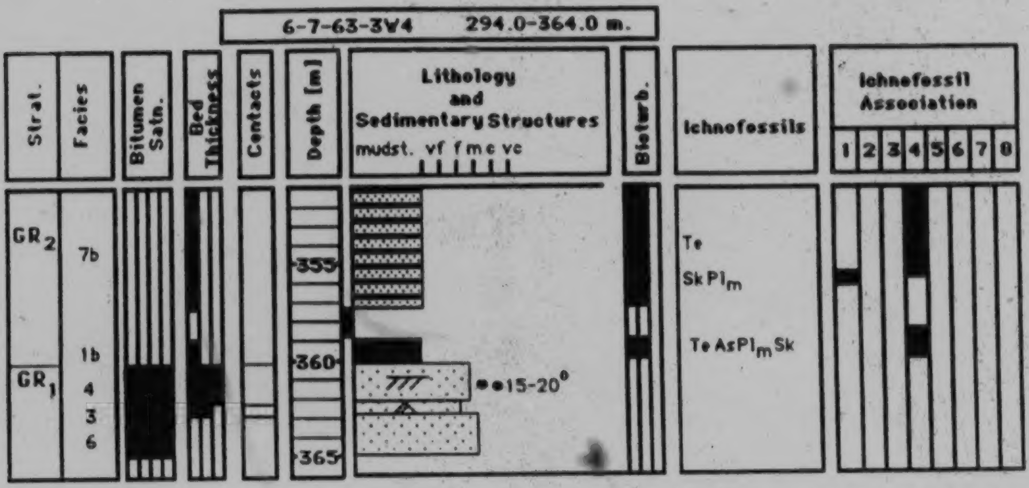

5-19-63-2W4 315.5-354.2 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR4
GR3
GR2
5
4
7a
3
1c
4
7a
4
7b
7a
1b
3
9
3
3
5
3
320
325
330
335
340
345
350
ptgs -c-
ptgs
ptgs
ptgs
-c-
ptgs
Pl_m Sk
SkCy Pl_m Pa Te
Pl_m
Pl_m Pa Sk
Te Pl_m Pa Cy Sk
Pl_m Pa Sk
Pl_m Sk
Pa
Pl_m Pa Cy Gy
Pl_m Pl_b Sk Cy
Pl_m Sk
Pl_m Sk Ro As

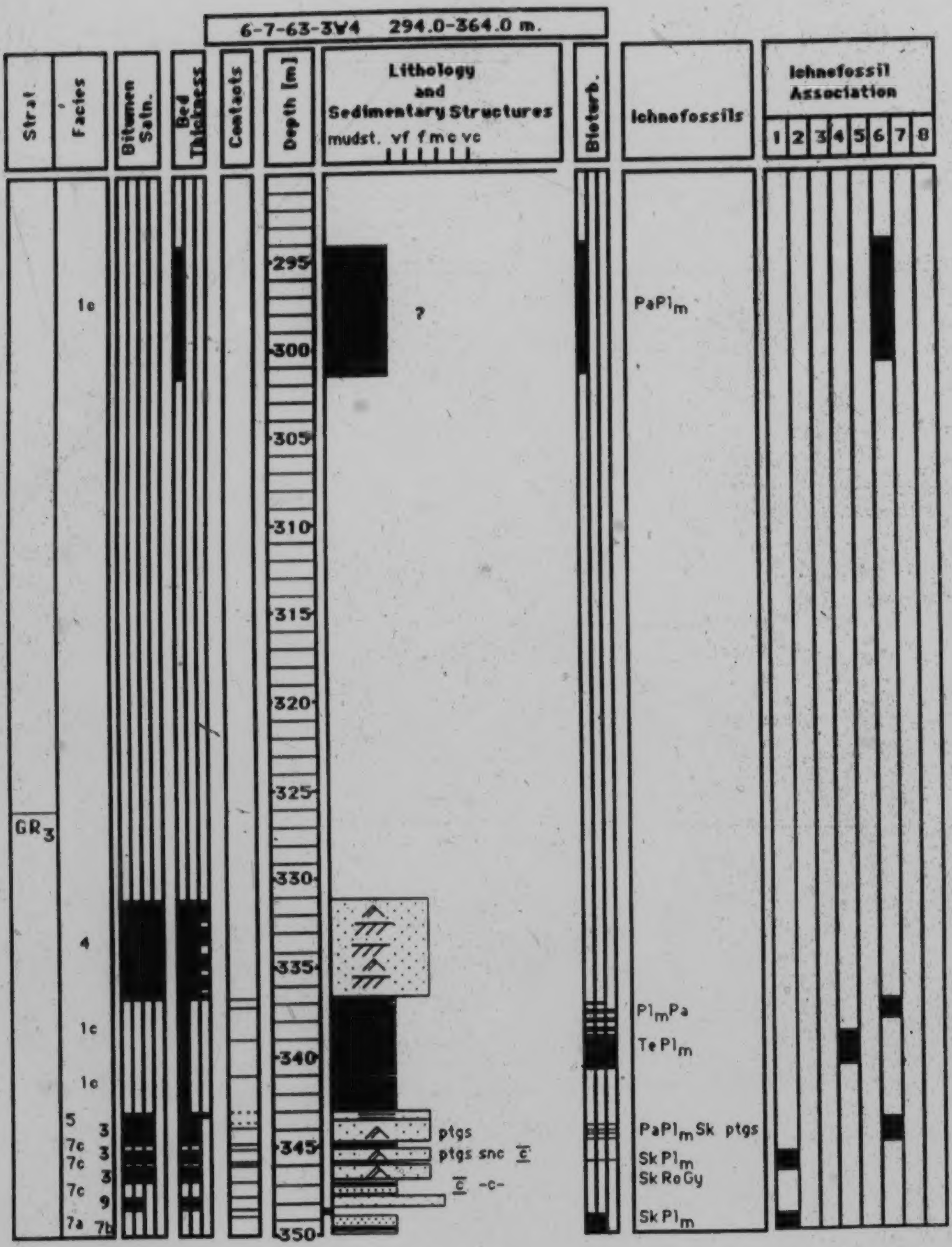

11-34-62-3W4 301.0-363.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR4
GR3
GR2
GR1
1d
3/4
7a
1b
4
6
6
6
6
6
6
7a
1d
7a
1d
4
3
1b
1d
1d
7c
4
1c
305
310
315
320
325
330
335
340
345
350
355
360
ptgs
ptgs
-c-
Ca
Ca
Ca
ptgs
c
ptgs
-c- c
Pl_m Sk
Pl_m Sk
Sk Pl_m Pa
Pl_m

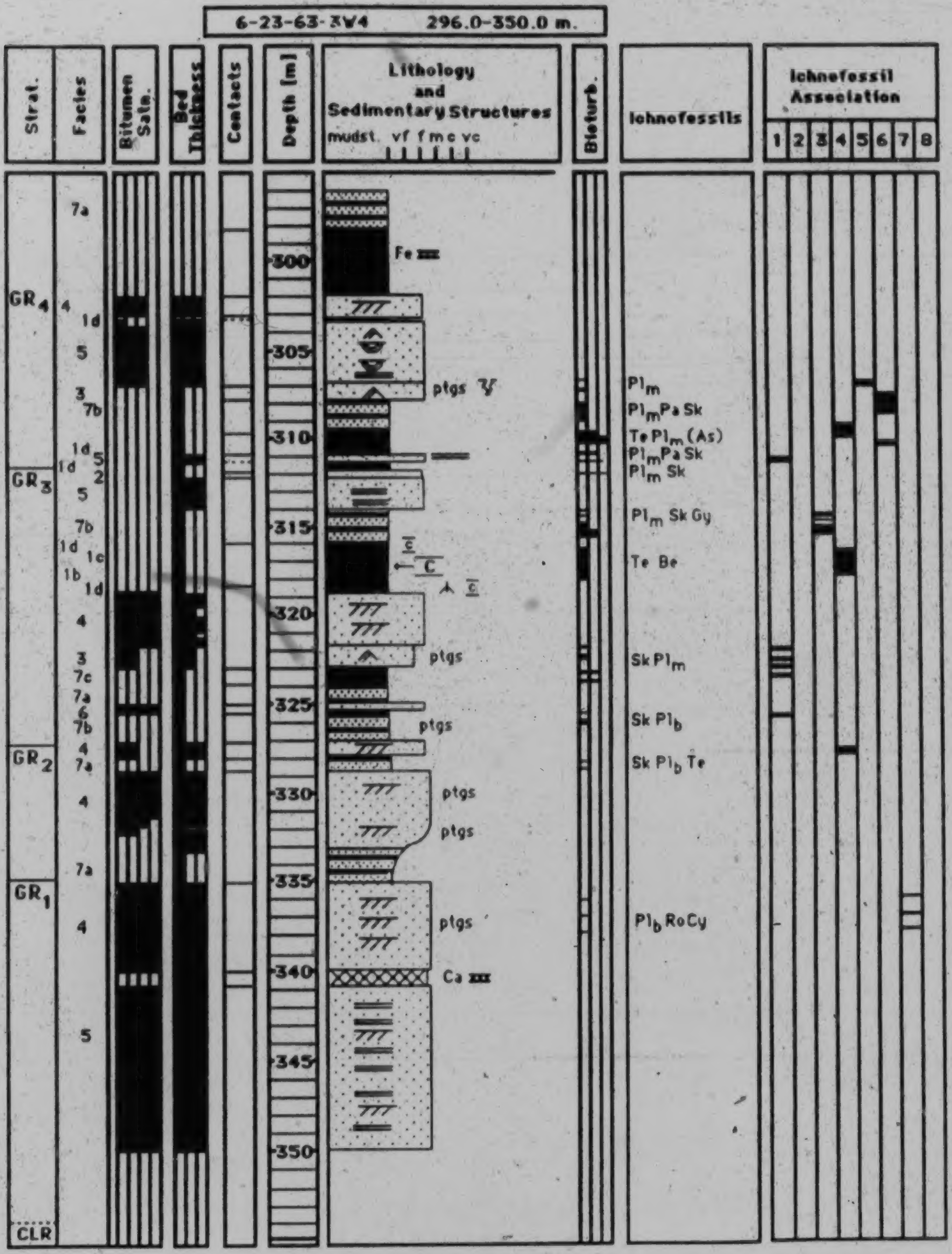

11-4-63-3W4 305.0-364.0 m
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR5
GR4
GR3
GR2
7c
1c
7a
1d
7a
3
1c
7b
4
5/4
4
3/4
4
4
5
7a 1d
1b
5
4
1b
1d
1b 1c
7c
6
1d
6
6
6
310
315
320
325
330
335
340
345
350
355
360
365
/5°
/6-10°
-c-
ptgs
ptgs
Pl_m Pl_b Te
Pl_m Te Sk Pa
Pl_m Fug
Sk Pl_m in ptgs
Sk
Pl_m Fug
Pl_m
Te Pl_m
Sk Pa Pl_m
Pl_m Pl_b Sk Te
As
Sk Cy Pl_m As
Sk Ro Pl_m
Sk Cy Ro Pl
in ptgs

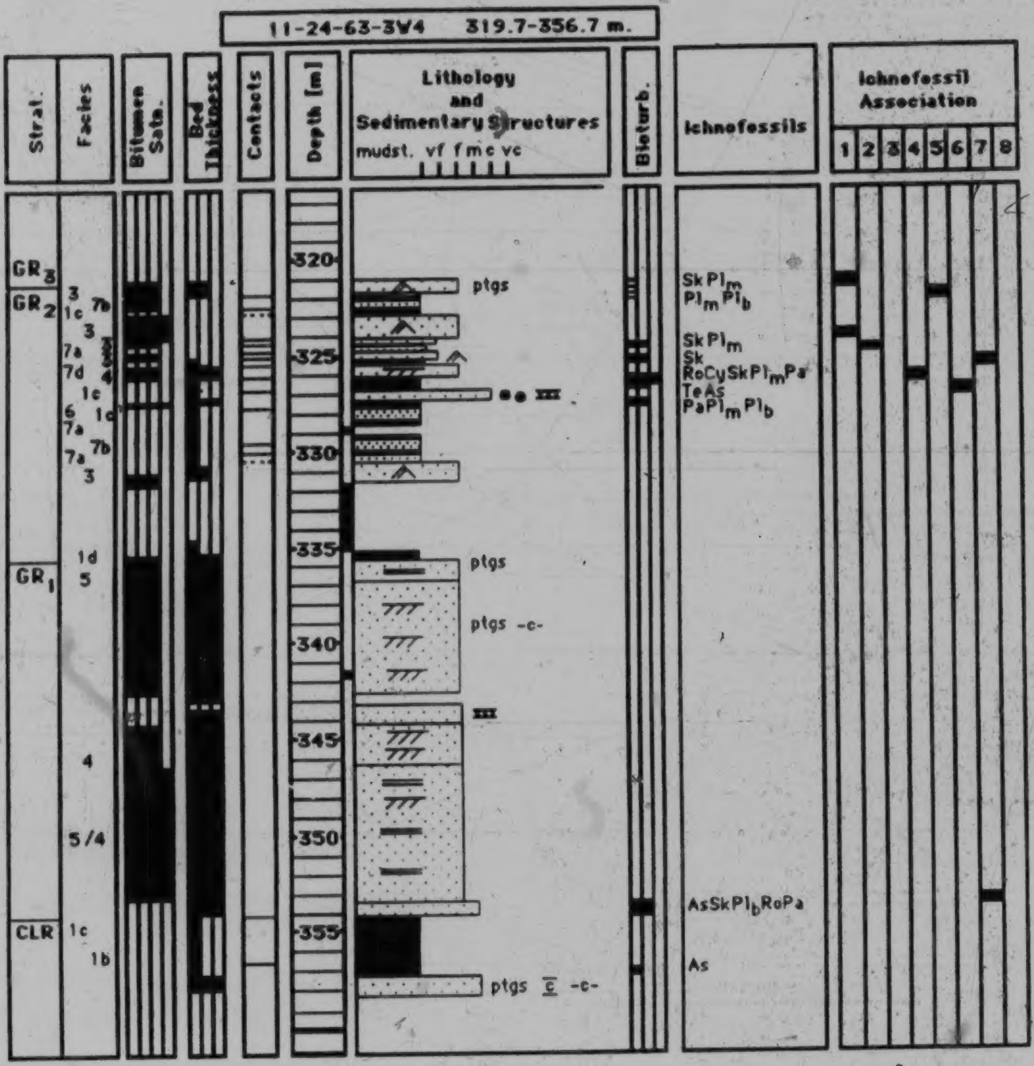

11-5-63-3W4 312.4-373.1 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR4
GR3
GR2
GR1
7b
3
6
1d
3
7a
3
7a
1d
3
4
1c
3
7c
3
7b
3
1c
3
5
315
320
325
330
335
340
345
350
355
360
365
370
ptgs
C
ptgs
ptgs
ptgs
o/w
Sk Pl$_m$ Pl$_b$
Sk Pa Pl$_m$ Pl$_b$
Te Sk Pl$_m$ Pa
Pl$_m$ Pa
Pl$_m$ Pl$_b$ As
Pa Pl$_m$ Sk
Pa Pl$_m$
As Pa Pl$_m$
Pl$_m$ Pa Sk
Pl$_m$ Pl$_b$
Pl$_m$ Pl$_b$ As
Pl$_m$

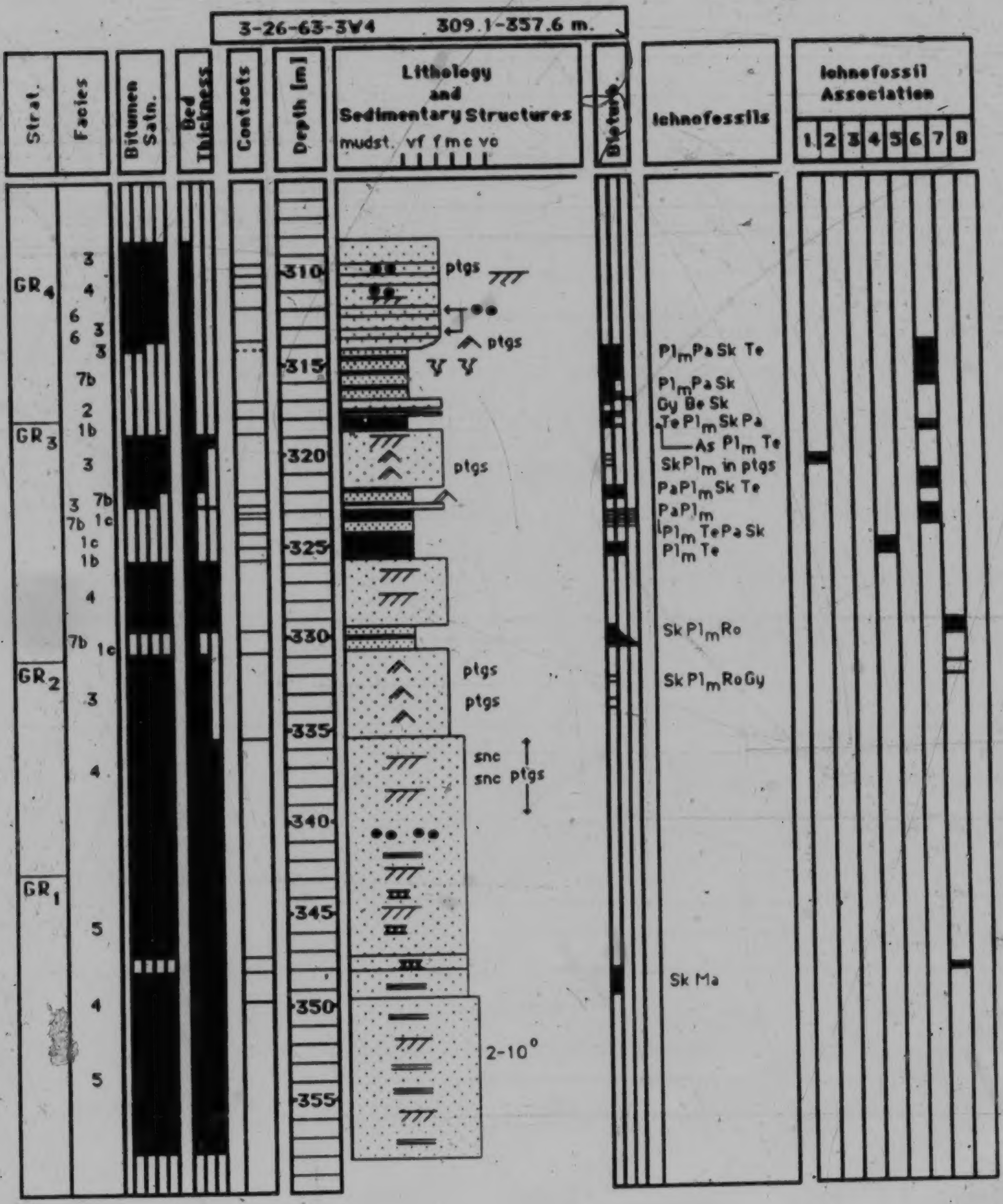

3-6-63-3W4 329.0-367.6 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR3
3
1c
7b
1c
GR2
3
3/4
(6)
GR1
330
335
340
345
350
355
360
365
ptgs
-c-
ptgs
Pl_m Sk Pa Te
Pl_m
Te Pl_m
Te
Pa Te As Sk Pl_m
in ptgs

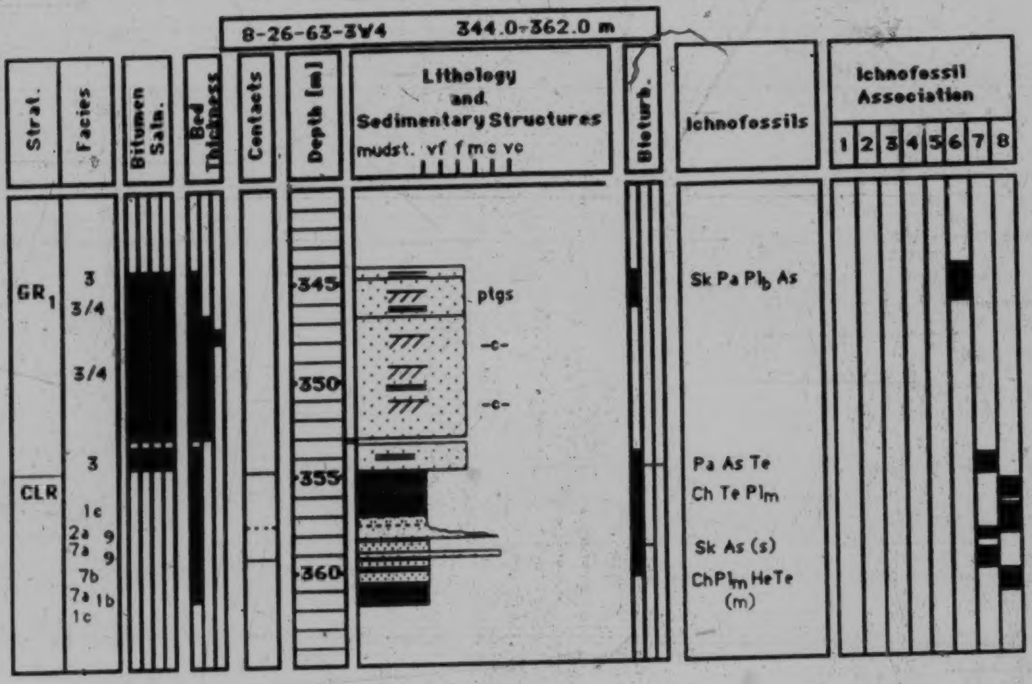

6-7-63-3W4 294.0-364.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR2
7b
1b
GR1
4
3
6
355
360
365
15-20°
Te
Sk Pl$_m$
Te As Pl$_m$ Sk


6-7-63-3W4 294.0-364.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
295
300
305
310
315
320
325
330
335
340
345
350
?
GR3
1e
4
1c
1e
5
3
7c
3
7c
3
7c
9
7a
7b
ptgs
ptgs snc c
c -c-
PaPlm
PlmPa
TePlm
PaPlmSk ptgs
SkPlm
SkRoGy
SkPlm


6-23-63-3W4 296.0-350.0 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR4
GR3
GR2
GR1
CLR
7a
4
1d
5
3
7b
1d
5
1d
2
5
7b
1d
1c
1b
1d
4
3
7c
7a
6
7b
4
7a
4
7a
4
5
300
305
310
315
320
325
330
335
340
345
350
Fe
ptgs
ptgs
ptgs
ptgs
ptgs
ptgs
Ca
Pl_m
Pl_m Pa Sk
Te Pl_m (As)
Pl_m Pa Sk
Pl_m Sk
Pl_m Sk Gy
Te Be
Sk Pl_m
Sk Pl_b
Sk Pl_b Te
Pl_b Ro Cy


11-24-63-3W4 319.7-356.7 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR3
GR2
GR1
CLR
3
1c
7b
3
7a
7d
4
1c
6
1c
7a
7b
7a
3
1d
5
4
5/4
1c
1b
320
325
330
335
340
345
350
355
ptgs
ptgs
ptgs -c-
ptgs c -c-
SkPlm
PlmPlb
SkPlm
Sk
RoCySkPlmPa
TeAs
PaPlmPlb
AsSkPlbRoPa
As


3-26-63-3W4 309.1-357.6 m.
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR4
GR3
GR2
GR1
3
4
6
6
3
3
7b
2
1b
3
3
7b
7b
1c
1c
1b
4
7b
1c
3
4
5
4
5
310
315
320
325
330
335
340
345
350
355
ptgs
ptgs
ptgs
ptgs
ptgs
snc
snc
ptgs
2-10°
Pl_m Pa Sk Te
Pl_m Pa Sk
Gy Be Sk
Te Pl_m Sk Pa
As Pl_m Te
Sk Pl_m in ptgs
Pa Pl_m Sk Te
Pa Pl_m
Pl_m Te Pa Sk
Pl_m Te
Sk Pl_m Ro
Sk Pl_m Ro Gy
Sk Ma


8-26-63-3W4 344.0-362.0 m
Strat.
Facies
Bitumen Satn.
Bed Thickness
Contacts
Depth [m]
Lithology and Sedimentary Structures
mudst. vf f m c vc
Bioturb.
Ichnofossils
Ichnofossil Association
1 2 3 4 5 6 7 8
GR1
CLR
3
3/4
3/4
3
1c
2a 9
7a 9
7b
7a 1b
1c
345
350
355
360
ptgs
-c-
-c-
Sk Pa Plb As
Pa As Te
Ch Te Plm
Sk As (s)
ChPlm HeTe (m)